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THESIS

STUDY OF TRANSPORTATION AND ITS PLANNING RESOURCES IN THE GERMAN JOINT SUPPORT SERVICE

by

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June 2010

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STUDY OF TRANSPORTATION AND ITS PLANNING RESOURCES IN THE GERMAN JOINT SUPPORT SERVICE

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requirements for the degree of

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Modeling and simulation provide an effective means by which to gain insight into the operational impact of different strategies. This research employs modeling and simulation to identify the significant factors for managing and allocating transportation assets in a humanitarian assistance scenario involving the German Joint Support Service. The U.S. Army Training and Doctrine Command (TRADOC) Analysis Center's prototype Logistics Battle Command (LBC) model is used for the exploration. The study outlines a methodology that draws on efficient experimental design and statistical analysis to determine which factors have the greatest affect on the overall performance of logistics operations. Some shortcomings in the LBC model are uncovered, but this study is able to provide limited insights about force structure and address how capability gaps and model shortcomings may be overcome.

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LIST OF ACRONYMS AND ABBREVIATIONS

ACT I	Advanced Concepts and Technologies International
AO	Area of Operations
BD	Brigade
BN	Battalion
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance
CAX	Computer Assisted Exercise
CBA	Capability-Based Assessment
CO	Company
DOE	Design of Experiments
DP	Design Point
DROPS	Demountable Rack Offload and Pickup System
EU	European Union
FCS	Future Combat System
FP	Force Protection
HQ	Headquarters
ISAF	International Security Assistance Force
JLTV	Joint Light Tactical Vehicle
JSS	Joint Support Service
LBC	Logistic Battle Command
LOGBASE	Logistics Base in Theater
MOE	Measure of Effectiveness
MP	Military Police
NATO	North Atlantic Treaty Organization
NOLH	Nearly Orthogonal Latin Hypercube
NSE	National Support Element
OSD	Office of the Secretary of Defense
POL	Petroleum, Oil and Lubricants
REC	Receiving Point
RHQ	Regional Headquarters

SPOD	Sea Port of Debarkation
STAN	Stärke- und Ausrüstungsnachweisung (see TO&E)
TFF	Turumba Freedom Fighters
TO&E	Table of Organization and Equipment
TRAC MTRY	TRADOC Analysis Center Monterey
TRADOC	U.S. Army Training and Doctrine Command
UN	United Nations
UNMIT	United Nations Mission in Turumba
VBA	Visual Basic for Applications

EXECUTIVE SUMMARY

Modeling and simulation provide an effective means by which to gain insight into the operational impact of different strategies for the management and allocation of transportation assets. This research explores a humanitarian assistance scenario involving the German Joint Support Service. The focus is on transportation and distribution operations from a seaport that provide aid to eight different receiving points via a theater logistics base. We employ a combination of modeling and simulation and statistical design of experiments to identify which are the significant factors for managing and allocating transportation assets. The scenario is implemented in a prototype version of the Logistics Battle Command (LBC) modeling platform developed by the U.S. Army Training and Doctrine Command Analysis Center in Monterey.

Ideally, logisticians should have a tool that facilitates rapid development of mission plans that reflect the commander's intent. The tool should also help them determine appropriate remedies in the face of unforeseen circumstances, such as weather delays, equipment failures, loss of materiel, and more.

The LBC model and the humanitarian assistance scenario are both quite complex, and we explored 131 factors to determine their relative impacts on three measures of effectiveness: (1) the average time to complete convoys between the sea base and the logistics base; (2) the average time to complete convoys between the logistics base and eight receiving points; and (3) the amounts of three commodities delivered. We used a highly efficient, custom-built experimental design due to the complexity of the factor space, and initiated 324 variations of the base scenario on high performance computers. Our original intent was to formulate recommendations for a suitable force structure for specific missions. However, significant shortcomings in the model were uncovered by our experimental design. In some cases, the root causes of these shortcomings could be identified and corrected by the lead programmers, but

others are still under investigation. This emphasizes the importance of systematically exercising a model, particularly when extending its scope to new domains.

Despite the issues uncovered during the LBC investigation, we are able to provide limited insights about force structure based on a deterministic analytic model that is prototyped in a spreadsheet. Specifically, because of the large number of transportation assets required to meet the demand, an enforced supply company is not recommended in this scenario. Instead, transportation companies have to be added to the force structure. This is also the simplest alternative from an organizational point of view. We conclude with some specific recommendations regarding the LBC model, along with topics for further research.

All logistic operations are highly important to any military mission. When using modeling and simulation techniques, as in this research, helping to increase the logistic efficiency is the main goal. At the end, logistics is not everything, but everything is nothing without logistics.

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I thank my thesis advisor, Dr. Susan M. Sanchez, for her support and guidance throughout the process of this research effort. I also thank Major Francisco Baez for introducing me to the LBC model and for patiently answering all questions; Mr. John Ruck, who was a great help with adjusting the model to my needs and debugging the model and the input files; and Mr. Stephen Upton, who made everything possible to run the LBC model on the high-performance computer. Furthermore, I thank Mr. Jonathan Shockley, who worked with me on the model and my scenario during the International Data Farming Workshop, and Mrs. Jane Wu, whose software tool saved a lot of time preparing the data files for analysis.

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I. INTRODUCTION

A. BACKGROUND AND THE OPERATIONAL PROBLEM

The German Armed Forces can deploy only after the German Federal Parliament makes the decision in accordance with the rules of the German law. Decisions concerning deployment of forces include issues such as the specific mission, tasks, objectives, the mission duration, the number and type of resources, and number or upper bound on personnel to deploy into the theater. Since the deployed forces are normally constrained by the number and type of resources and personnel available for the mission, resource planning and utilization is difficult. This issue becomes more complex when the unit home-structure organization cannot meet the increased demand of supplies or move those supplies in support of the geographic commander's mission requirements. Consequently, to meet those requirements decision makers typically tailor packages of a distinct type and number of resources and personnel, and the command hierarchy and relationships that may differ from their home structure or organization. In the early stages of planning for an upcoming deployment of forces, analysis to support the planning and utilization of resources and personnel provides a means to inform decision makers as well as evaluate potential futures.

The German Joint Support Service (JSS) is responsible for all supporting activities of the different branches of the German Armed Forces (i.e., Navy, Army, and Air Force). One primary activity of the JSS is providing logistics from Germany into a mission theater up to the point where supplies are delivered to the theater logistic assets of the different branches. Once the supplies arrive in theater, logistics soldiers maintain equipment, process supplies, and form logistics convoys to deliver those supplies to the logistic assets of the different branches. The core logistics functions are supply, maintenance, and transportation.

In today's irregular operating environment, a logistical convoy's actual size depends on the mission, enemy, terrain and weather, troops and support available, time available, and civil considerations. Some additional factors that impact the actual size of the logistics convoys are the forecast, based on the different units' consumption, as well as the travel distance, the travel time, and how long it will take to offload the supplies. Empirical data for the last nine years provides evidence that soldiers conducting logistics convoys in theater are vulnerable because the enemy actively hunts high-payoff targets such as logistics convoys. Consequently, logistics convoys must include Military Police (MP) security vehicles, force protection vehicles, and medical support personnel with their associated vehicles. In order to perform logistics functions efficiently in an uncertain environment, the JSS and German logistics personnel must make informed decisions for transportation and the planning and utilization of supporting personnel resources.

B. THESIS OVERVIEW

The purpose of this thesis is to show how to use modeling and simulation, combined with design of experiments techniques, to assess the operational effectiveness of different strategies of transportation, supporting personnel resources planning and utilization, and the impact of those strategies on logistics functions.

As a proof of principle, this effort explores the use of the Logistic Battle Command (LBC) Model combined with an efficient space-filling experimental design to conduct a robust analysis. The scenario is designed to provide a reusable framework in order to explore different strategies. Furthermore the significant factors with the greatest impact on the overall performance are identified so that insights for the development of future missions are possible. For this, a generic scenario will be derived from a Chapter VII—Resolution of the UN Security Council as well as a notional decision of the German government.

The following questions are the issues for analysis and they provide the direction of the research:

- What is the most efficient method of transportation and supporting personnel resources planning and utilization in the execution of logistics functions?
- What is the best approach between (1) augmenting the logistics battalion with an additional transportation company, and (2) augmenting a supply company of the logistics battalion with platoons of the transportation company?
- What is the best technique for allocating personnel to the vehicles conducting logistics convoys?

The results of this research show how transportation, and therefore German logistics, can be improved by identifying effective methods for planning and utilizing the transportation resources and supporting personnel. Effective and reliable logistics operations have to be performed on time by efficiently utilizing all existing resources without creating shortfalls or increasing cost. Answering the research questions could provide insight and a framework for planning and conducting future operations in a more efficient way.

This introductory chapter is followed by a brief literature review and background information in Chapter II. Chapter III describes the LBC model, the instantiated scenario, and the research constraints, limitations and assumptions. Chapter IV covers the Measures of Effectiveness (MOE) and the Design of Experiments (DOE) developed and used to address the research questions. Chapter V details the analysis of the simulation output. Finally, Chapter VI provides conclusions and recommendations derived from the analysis.

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II. LITERATURE REVIEW

This chapter gives an overview of the laws, procedures and policies of deploying German Armed Forces, distribution operations, and Table of Organization and Equipment (TO&E) existing or in development.

A. LEGISLATION AND ARMED FORCES

Germany's Basic Constitutional Law, Grundgesetz für die Bundesrepublik Deutschland (1949), defines the establishment of military forces in Article 87a. Without further laws, German Armed Forces may not act outside Germany's territory. In order to act outside Germany's territory under the control of NATO, the UN or the EU, this loophole in the legislation had to be closed.

In 2005, the Law on Parliamentary Involvement in the Decision to use Armed Forces Abroad, Gesetz über die parlamentarische Beteiligung bei der Entscheidung über den Einsatz bewaffneter Streitkräfte im Ausland (2005), was finally enacted. Paragraph 3 of that law states that any planned deployment of the German Armed Forces must be requested by the German Federal Government to the German Federal Parliament. A request must include the following details:

- the mission,
- the area of operation,
- the legal foundation of the mission,
- the maximum number of personnel,
- the skills and abilities of the deployed forces,
- the planned time for the mission, and
- the planned costs and funding.

Whenever details of the request change, the request must be resubmitted. The request does not take force structures into account, so the maximum number of personnel requested for a mission does not correspond to the existing TO&E of the German Armed Forces. Thus, the military planning staff has to decide which forces will be deployed given the restrictions of the decision of the German Federal Parliament. For example, the German troop strength request for the ISAF mission in 2007/2008 was a total number of 3,500 personnel (German Federal Government, 2007).

B. GERMAN JOINT DISTRIBUTION OPERATIONS

Starting with the transformation of the German Armed Forces in the early 2000s, all logistic planning and execution activities were rearranged. All logistic functions, which were common in the three German branches of the Armed Forces (i.e., Navy, Army and Air Force), were carried over to the newly constructed Joint Support Service. One of the main responsibilities of the Joint Support Service is the distribution of supplies from Germany to the forward logistic base in theater, where the logistic forces of the branches take over from the Joint Support Service (The Joint Support Service, 2007).

Due to the transformation and the corresponding change on the force structure, existing policies were nullified. In order to develop new and up-to-date policies and publications, the Joint Support Command ordered an exercise series called JOINT LOGISTICS. The plan is for this exercise to be conducted every two years, with different contents, as a computer-assisted exercise (CAX) as well as an exercise for troops down to the company level. The results from these exercises form the basis for the development of future logistic publications of the German Armed Forces.

Up until now, this publication has not been enacted; and for each mission planned, the logistics support is tailored to the mission within the operations plan.

C. GERMAN JOINT SUPPORT SERVICE TRANSPORTATIONS AND LOGISTICS FORCE STRUCTURE

For all German forces down to the company level, the Stärke- und Ausrüstungsnachweisung (STAN) is issued. The equivalent of this in U.S. forces is the TO&E. The STAN is a working document in which changes can be requested and is subject to a regular revision by a commission. When planning the forces needed for a mission, the STAN is a basic document and often the forces in a mission will be made up from companies in their described structure with their described equipment. But, as every mission will be tailored to the special needs and the decision of the German Federal Parliament must be met, the given structure and equipment may be changed.

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III. LOGISTICS BATTLE COMMAND MODEL AND SCENARIO

A. THE LOGISTICS BATTLE COMMAND MODEL

The Logistics Battle Command (LBC) model is a closed-form, discrete event, high-resolution and stochastic simulation focusing on logistics, developed by the TRADOC Analysis Center – Monterey (TRAC MTRY). It is programmed in JAVA and based on Simkit (Buss, 2001).

There are two main areas of interest for using the LBC model: forecasting demand, as well as planning and executing the distribution operations. The LBC has two main features. One feature of the model is to dynamically forecast and represent demand for petroleum, oil, and lubricants (POL), ammunition, and medical supplies; the other feature is to represent the distribution network by including nodes and arcs in a scenario. Nodes represent storage areas for the different types of supplies, maintenance and supply service locations, etc.; arcs represent the routes on which the supplies are transported.

The LBC can operate either connected to the Combat XXI model or, as in this thesis, as a stand-alone model. Connected to a combat model, the LBC will receive usage data from the other model and give it back the sustainment data. When used as a stand-alone model, it can use forecasted data, data from earlier runs of the simulation, or historical data to analyze a broad spectrum of logistical issues. The model uses networks to represent the end-to-end-flow of supplies.

The transportation network links the LBC model to an area of operation representing the geographical distribution of supplies by the user-defined nodes and arcs, and allows dynamic route planning. The communication network represents all communication taking place during the mission. It connects all levels in the force structure, ensuring information flow within the network and linking the planning and transportation networks. Finally, the planning network links planning of the distribution operations to its execution and allows monitoring of the execution, so re-planning is possible when execution does not follow planning.

The input file for the LBC model is an XML file that is generated from an Excel workbook. The Excel workbook consists of twenty-seven spreadsheets in the latest stand-alone version. These spreadsheets contain all the information needed to execute a scenario. The spreadsheets used in this research are the following:

- *ScenarioData* — Within this spreadsheet, which drives the simulation, the scenario length and the number of replications are defined. Furthermore, the user specifies whether the LBC model runs as a stand—alone model or integrates in another model (e.g., Combat XXI).
- *ForceStructure* — This spreadsheet defines the number and types of systems in each unit.
- *ConsumableType* — The types of consumables (e.g., supplies) are defined here.
- *TransportationType* — This spreadsheet defines the type of transportation assets and its capacity.
- *TransTypeConsumableType* — This spreadsheet defines which transportation type can transport which amount and type of consumable.
- *PeriodicConsumptionLogic* — This spreadsheet defines how much and what consumables each unit consumes at each event.
- *SimpleProvider* — This spreadsheet lists all providers and consumers in the scenario.
- *SimpleProviderConsumables* — This spreadsheet defines the initial stock of each consumable in every unit.
- *RandomTransportationArrivalProb* — Within this spreadsheet, the probability of arrival on every arc is defined.

- *RandomTransportationDelay* — This spreadsheet defines the distribution used for the time it takes to get from one node to another.
- *FormConvoy* — This spreadsheet defines the composition (e.g., type and number of the vehicles, trailers and drivers) of the convoys used in the scenarios.
- *Upload* — This spreadsheet defines which consumable and how much of it will be loaded onto a convoy.
- *Move* — This spreadsheet describes the movement of a convoy.
- *Download* — From the information of this spreadsheet, a convoy gets unloaded at its current location.
- *DisbandConvoy* — This spreadsheet information adds the assets of the convoy to their owning unit at the current location and makes them available for a new convoy.
- *SeizeAssets* — This spreadsheet information seizes supporting assets to unload or download a convoy.
- *ReleaseAssets* — This spreadsheet information releases the assets seized to upload or download a convoy.
- *End* — The information given in this spreadsheet indicates the end of a plan.
- *EndPlay* — The information given in this spreadsheet indicates the end of a play.
- *Plan* — This spreadsheet defines the names of the plan(s).
- *TaskNodeDuration* — This spreadsheet defines the distribution of how long it takes to execute each plan.
- *PrecedenceArc* — This spreadsheet defines the order of the plans and which plays to execute on execution of a plan.
- *Play* — This spreadsheet defines the task network (i.e., the order of events occurring in a play).

- *Output* — This spreadsheet determines which outputs are generated during each run of the simulation.

Further details can be found in the LBC Users Guide v3.9.0 (DRAFT), (TRAC-MTRY, March 2009).

B. SCENARIO

The purpose of this thesis, as stated in Chapter I, is to assess the operational impact of different strategies for the management and allocation of transportation assets and the resulting impacts of those strategies. Therefore, the base scenario needs to focus on a high emergence of transportation, which is more likely given in a peacekeeping operation combined with humanitarian assistance.

1. The Mission

The population of the (notional) far eastern country of Turumba suffers from fights between two religions, represented by the Turumba government and a rebel group called "Turumba Freedom Fighters" (TFF). Both parties have agreed to a peace treaty under the control of the United Nations. A Chapter VII UN resolution by the Security Counsel has approved a peacekeeping force of the international community, United Nations Mission in Turumba (UNMIT).

The United States of America and Germany are the main troop contributors in the mission. Germany is responsible as the National Support Element (NSE) for the German troops, and is in charge of the humanitarian relief actions in northern Turumba. This includes the replenishment of bottled water, medical supplies, non-military goods (e.g., tents, building material, etc.) and spare parts for two provincial reconstruction teams and six villages and cities. The U.S. is in charge of its own logistics, and provides the troops responsible for monitoring the peace treaty. Supplies come into Turumba either by ship to the port of Turum, which is the seaport of debarkation (SPOD), or by air from outside the country. U.S. forces operate convoy rest and maintenance areas.

2. The Country of Turumba

Turumba is a far eastern country with a moderate climate. The area of Turumba is about 650,000km^2; its east-west dimension is 1,000km and the north-south dimension 900km. Mountains and valleys to a height of 7,500m dominate the northern part of Turumba; the southern part is mainly hilly and dry. Three countries border Turumba, in the east, west and north. The south of Turumba borders the ocean.

Turumba's population consists of nearly twenty-five million inhabitants, of which approximately one-third are Christian and two-thirds are Muslim. The capital, Turum, lies in the southwest, where the main port of Turumba is located.

3. Force Structure of German UNMIT Forces

The force structure of the German UNMIT forces differs from the given force structure in the TO&E as discussed in Chapter I. In order to assess the impact of different strategies for the management and allocation of transportation assets, different force structures have to be evaluated. The force structures used in this research are shown in Figures 1–4.

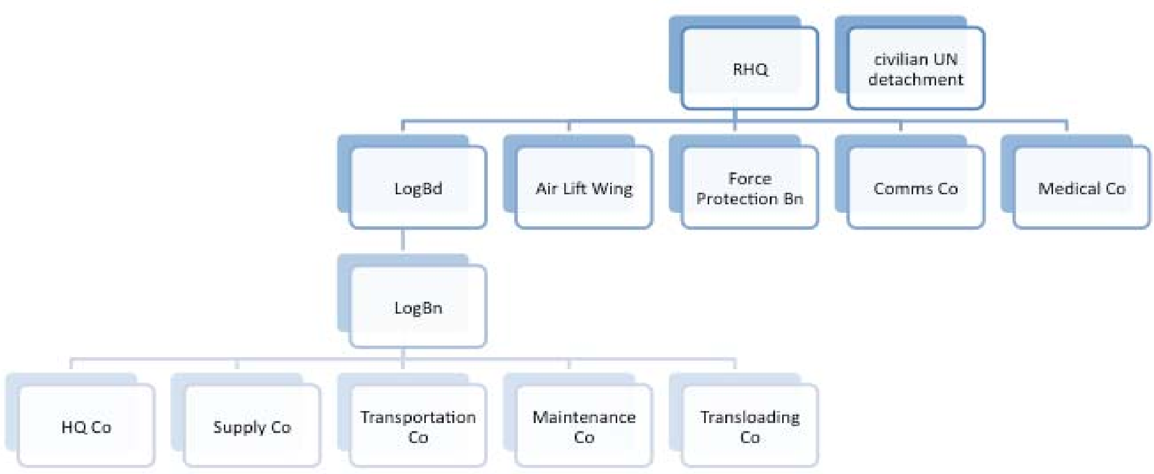


Figure 1. Force Structure with Transportation Company and Brigade-level Planning Cell

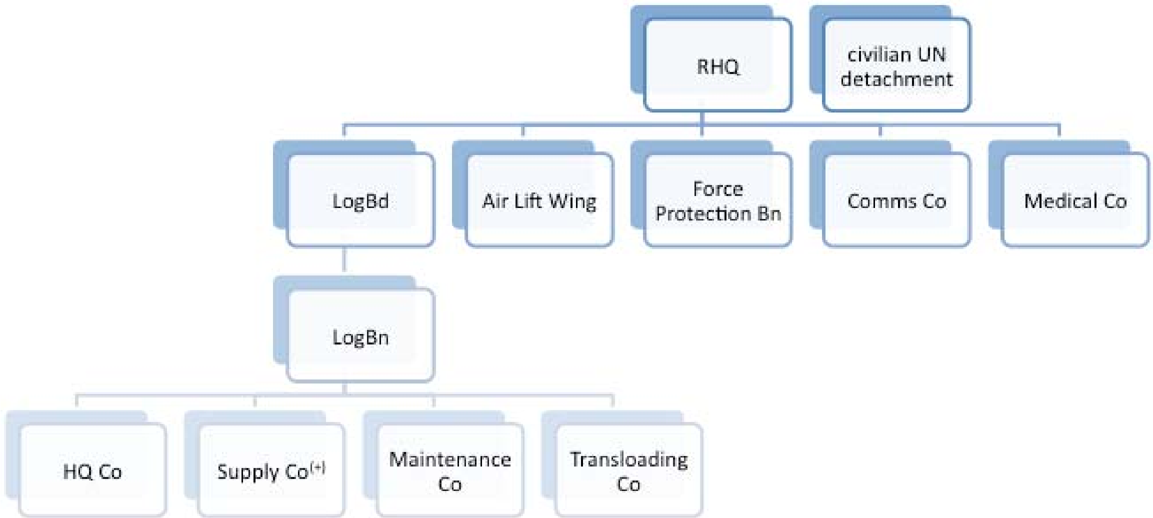


Figure 2. Force Structure without Transportation Company and with Brigade-level Planning Cell

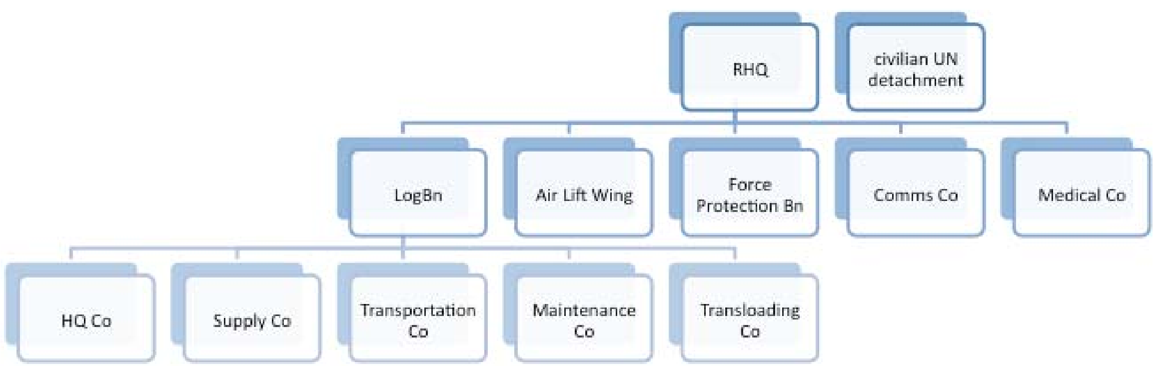


Figure 3. Force Structure with Transportation Company and without Brigade-level Planning Cell

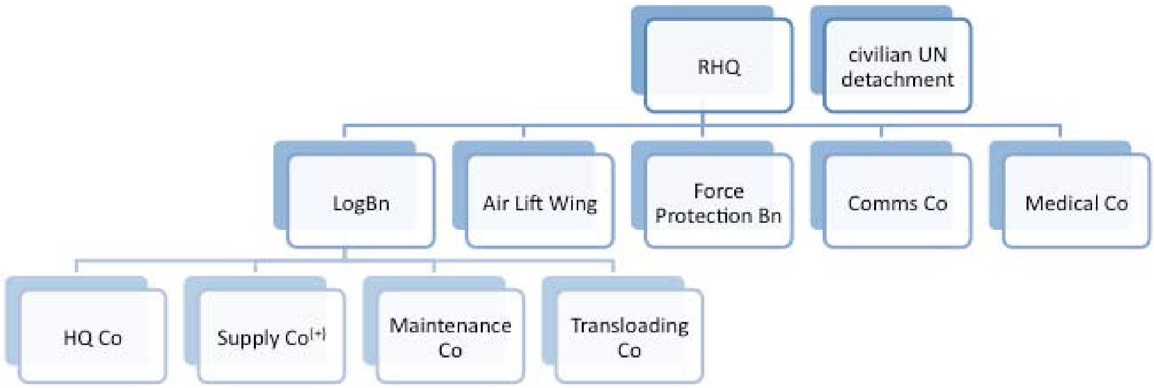


Figure 4. Force Structure without Transportation Company and without Brigade-level Planning Cell

4. Locations, Distances and Population in Turumba

All of the German UNMIT forces are located in the northern part of Turumba in the logistics base in theater (LOGBASE), except for the transloading company that operates at the sea port of debarkation (SPOD) in Turum. Due to restricted operating hours for the drivers, stops are necessary when traveling from the LOGBASE to the SPOD and back.

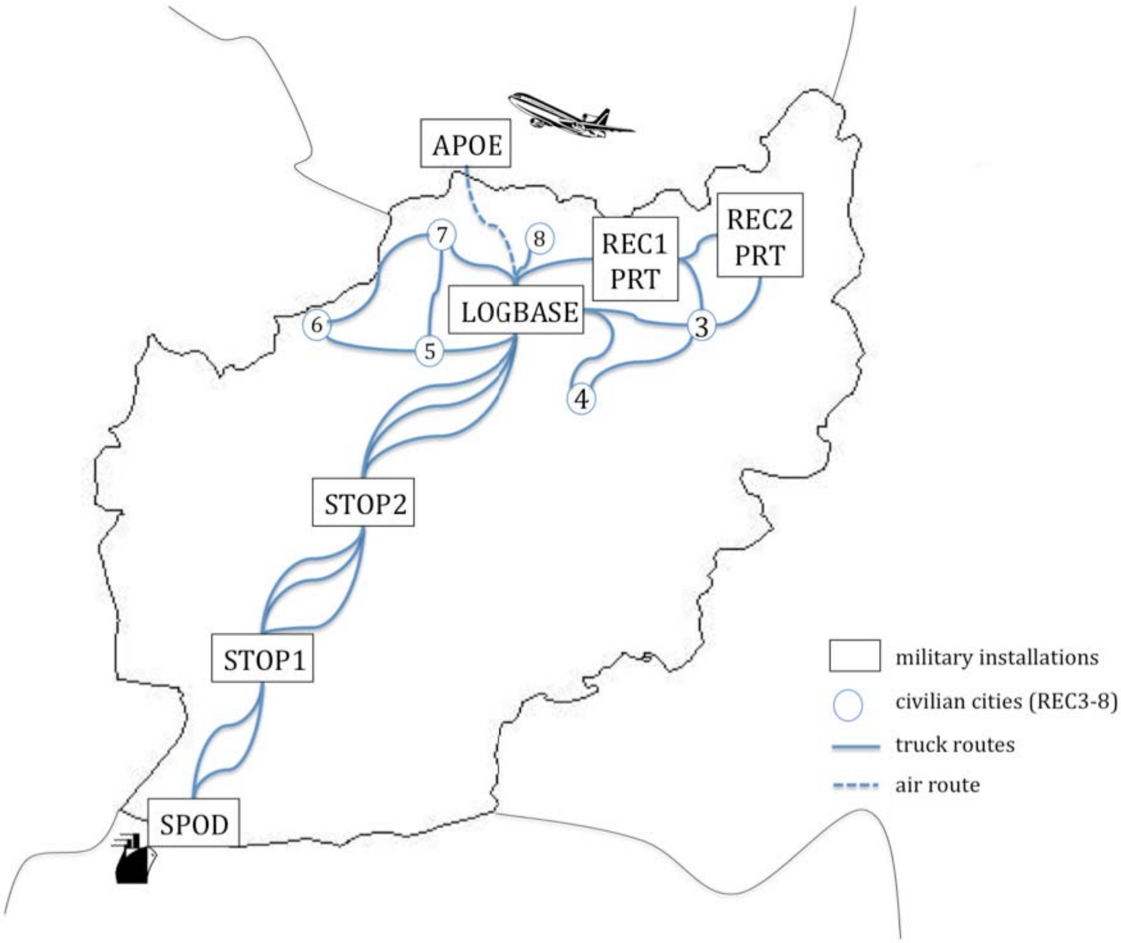


Figure 5. Map of Turumba and Locations

The distances between all locations of concern are given in Table 1. The travel time is calculated by the distance, the average speed of the convoys, and the required rest time of the drivers during travel.

From	To	Distance (in km, depending on possible route)
LOGBASE	SPOD	795 - 850
LOGBASE	REC1PRT	150
LOGBASE	REC2PRT	310 - 340
LOGBASE	REC3	225
LOGBASE	REC4	115
LOGBASE	REC5	160
LOGBASE	REC6	285 - 345
LOGBASE	REC7	160 - 295
LOGBASE	REC8	100

Table 1. Distances in Turumba.

The demands in the military installations and villages are calculated using the population sizes and the average demand of the supplies on a daily basis. These are 6kg/person/day for water, 0.2kg/person/day for medical supplies, 4kg/person/day for non-military supplies and 3kg/soldier/day for spare parts. These figures are reflected in Table 2. In the simulation, these daily demands are factors.

Name	Population	Demand (water)	Demand (medical supplies)	Demand (non-military)	Demand (spare parts)
		all numbers in kg			
LOGBASE	400	2400	80	0	1200
SPOD	80	480	16	320	0
REC1PRT	4030	24180	806	16120	0
REC2PRT	5530	33180	1106	22120	0
REC3	3000	1000	600	12000	0
REC4	1500	9000	300	6000	0
REC5	1000	6000	200	4000	0
REC6	4000	24000	800	16000	0
REC7	4500	27000	900	18000	0
REC8	800	3000	100	2000	0

Table 2. Population and Daily Demand on Supplies

C. TRANSPORTATION NETWORK

The transportation network, which links the real area of operations (AO) to the LBC model, is used to model all necessary tasks in order to distribute all supplies from the SPOD to the receiving points (REC1PRT through REC8 as in Table 2). For the model to work correctly, the spreadsheets TaskNodeDuration, PrecedenceArc and Play are essential.

The transportation networks shown in Figures 6 and 7 represent the scenario that is implemented in the LBC model. Figure 6 represents the tasks to plan the resupply and move and transport the supplies from the SPOD to the LOGBASE. After planning has finished, orders are given to the executing companies, the convoy is formed and it moves from the LOGBASE to the seaport. After being loaded, the convoy moves back to the LOGBASE and gets unloaded; the transportation assets are available again. During loading and unloading, the needed assets (e.g., personnel, forklifts and container-handling equipment) are seized from the available assets.

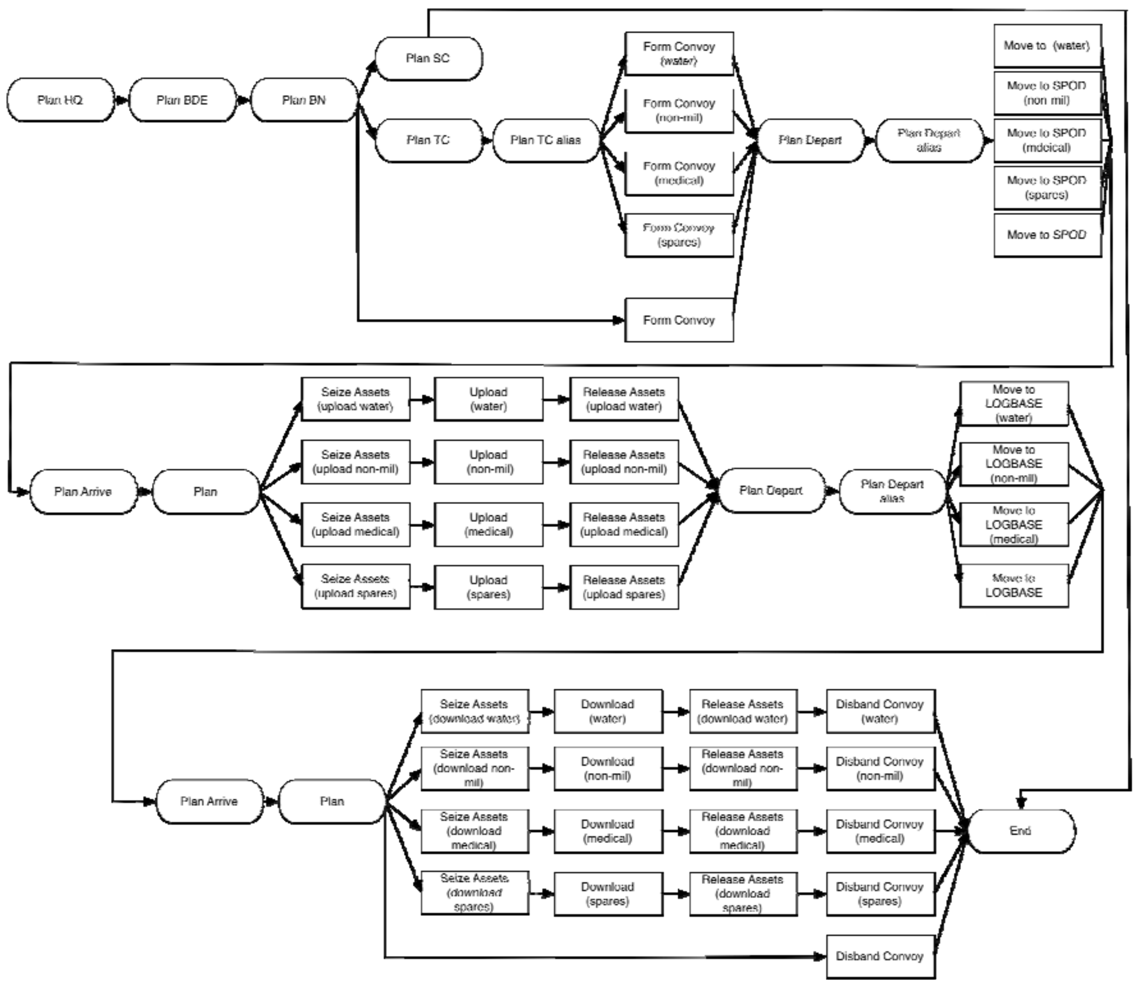


Figure 6. Transportation Network Diagram: SPOD to LOGBASE

Figure 7 shows the distribution of the supplies from the LOGBASE to the eight receiving points. After planning takes place, orders are given to the companies who will form the convoys and load them. Each convoy moves to their ordered destination—one of the eight receiving points—and will be unloaded; afterwards the convoy moves back to the LOGBASE and will be available again. Assets for loading and unloading the convoys are also seized and released as needed.

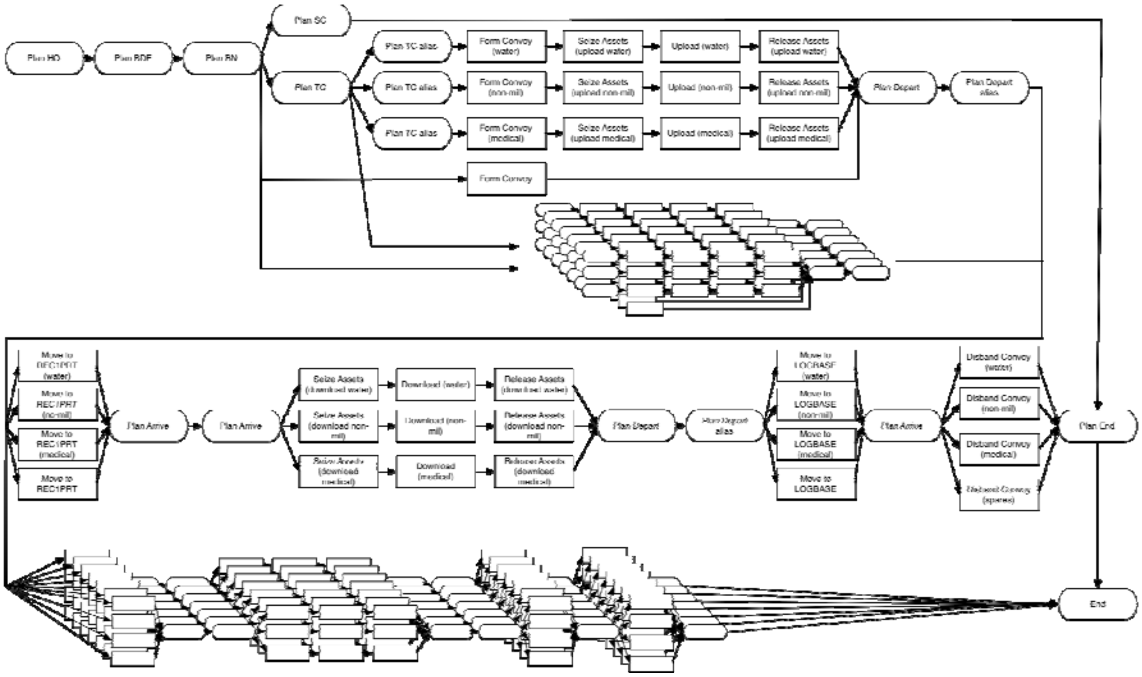


Figure 7. Transportation Network Diagram: LOGBASE to Receiving Points

D. CONSTRAINTS, LIMITATIONS AND ASSUMPTIONS

This sections deals with the constraints, limitations and assumptions used in this research.

1. Constraints

There are no constraints within this research.

2. Limitations

Several limitations apply:

- Currently there is no integrated design of experiments in the LBC model that allows for quick examination of alternatives.

- The task network only allows for four tasks: plan, upload, move and download. The order of upload, move and download cannot be changed.
- The time for uploading and downloading is a user input based on experience of subject matter experts.

3. Assumptions

The following are the assumptions made in this study.

- The focus is on transportation in a humanitarian relief scenario, attrition by enemies is not an issue. Therefore, the number of accompanying vehicles (i.e., force protection, MP and medical vehicles) in a convoy will not change.
- Planning times start with receiving orders from the UN HQ and end with forming the convoys.
- Transportation times start with forming the convoys and end with disbanding the convoys.
- Route selection of the convoys is given by the distribution of movement time.
- All vehicles have sufficient operational hours before the next planned maintenance.
- All vehicles have their trailer or flatrack available at all times.
- The convoys will be composed out of a changing number of transportation vehicles, but the accompanying vehicles are always:
    - one leading vehicle of type WOLF;
    - two Force Protection vehicles of type DINGO;
    - two Military Police vehicles of type DINGO; and
    - one Medical vehicle of type FUCHS.
- Supply of all commodities at the SPOD is infinite.
- The force structure is not modeled directly, but can be inferred by the values of the number of planning personnel, number of

transportation vehicles and transloading assets. Given a number of these assets the force structure, i.e., the number of platoons and companies can be calculated due to the structure given in the TO&E.

IV. MEASURES OF EFFECTIVENESS AND DESIGN OF EXPERIMENTS

In this chapter, we first discuss the measures of effectiveness, followed by the chosen design of experiments including the development of the design points and an explanation of the factors. At the end of this chapter, we discuss the implementation of the scenario into the LBC model and the execution of the simulation.

A. MEASURES OF EFFECTIVENESS

Three measures of effectiveness are used to answer the research questions: times needed to conduct the transports, and the delivered commodities. All MOEs are measured over the entire simulation time of 9,600 hours.

1. MOE 1: Time of Convoy 1 (LOGBASE - SPOD - LOGBASE)

The time of every supply convoy is a summation of several components.

- The time to form the convoy (i.e., the transportation platoons receiving their orders and acquiring the ordered vehicles, trailers/flatracks and drivers).
- The time to travel from the LOGBASE to the SPOD.
- The time to load the convoy (i.e., the time needed to acquire the necessary loading assets (forklift for spare parts, container-handling equipment for water, medical supply and non-military supplies) and meet with the accompanying vehicles from the medical, force protection and MP units).
- The time to travel from the SPOD to the LOGBASE.
- The time to rest, as the maximum number of hours a driver may drive due to German law (Kraftfahrvorschrift für die Bundeswehr) is nine hours per day.

- The time to unload the convoy either at the LOGBASE or the receiving point.
- The time to disband the convoy (e.g., conduct the regular checks after use of the vehicles, refuel, etc.).

The goal is to keep this MOE at a minimum while meeting the logistics demand.

2. MOE 2: Time of Convoy 2 (LOGBASE - RECs - LOGBASE)

The time of every distribution convoy is also a summation of several components.

- The time to form the convoy (i.e., the transportation platoons receiving their orders and acquiring the ordered vehicles, trailers/flatracks and drivers).
- The time to load the convoy (i.e., the time needed to acquire the necessary loading assets (forklift for spare parts, container-handling equipment for water, medical supply and non-military supplies) and meet with the accompanying vehicles from the medical, force protection and MP units).
- The time to travel from the LOGBASE to the receiving points.
- The time to unload the convoy at the receiving points.
- The time to travel from the receiving points to the LOGBASE.
- The time to rest, as the maximum number of hours a driver may drive due to German law (Kraftfahrvorschrift für die Bundeswehr) is nine hours per day.
- The time to disband the convoy (e.g., conduct the regular checks after use of the vehicles, refuel, etc.).

The goal is to keep this MOE at a minimum while meeting the logistics demand.

3. MOE 3: Delivery of Commodities

The delivery of commodities is measured by the fraction of time within the simulation time where the stocklevels of the three types of commodities are zero.

These times are taken from the stocklevel output of the LBC model. The goal is to keep the times where the stocklevels are zero to a minimum.

B. DESIGN OF EXPERIMENTS

This research makes use of a design of experiments that is capable of addressing a large number of factors in order to explore the LBC model results and to assess if and how changing input parameters affect the model's output. The DOE used is based on the Nearly Orthogonal Latin Hypercube (NOLH), which is explained later on in this chapter. The design generally consists of a matrix where columns are formed by the factors, and the design points form the rows. The levels (or values) of the factors vary in each column across a specified range of interest to the analyst (e.g., determined by the force structure). The output of the LBC model is subsequently used to analyze which decision factors have significant effects on the MOEs in order to answer the research questions.

A total of 131 factors are used in this research's DOE. They are divided into two general groups: decision factors and noise factors. Decision factors are factors that can be controlled by actions of the decision makers. Therefore, they are also known as controllable factors. In contrast, noise factors, or uncontrollable factors, are factors that either the decision maker cannot control or that only can be controlled at a very high expense in the real world. However, one could also benefit by observing the influence of the noise factors on the experiment outcome (Sanchez, 2000).

Table 3 gives a summary overview of the factors used in this research where each factor is put into a category. Note that some factors are continuous or essentially continuous, while others can take on only a limited number of discrete levels.

Category	Number of factors	Number of decision factors	Factor number	Number of noise factors	Factor number	Number of levels (min and max)
Force Structure	28	28	1 - 28	0	-	2 - 90
Demand	12	0	-	12	1 - 12	21 - 2000
Convoy	28	28	29 - 56	0	-	2 - 4
Transloading assets	56	32	57 - 88	24	13 - 36	6 - 40
Probabilities	7	0	-	7	37 - 43	21 - 81
Total	131	88	-	43	-	

Table 3. Overview of Factors

1. Detailed Factor Descriptions

We now provide detailed descriptions of all 131 factors. Except for the probabilities and the demand, all factor levels are Integers.

a. Decision Factors

(1) *BDE planning personnel* — This discrete factor represents the number of personnel in the transportation planning cell at the brigade level, ranging from 1 to 23.

(2) *BN planning personnel* — This discrete factor represents the number of personnel in the transportation planning cell at the logistics battalion level; it ranges from 14 to 20.

(3) *Supply Coy planning personnel* — This discrete factor represents the number of personnel in the planning cell of the supply company, the range is between 5 and 7.

(4) *Supply Coy DROPS trucks* — This discrete factor represents the number of DROPS trucks within the supply company, capable of carrying up to 14 tons of supplies on flatracks. It ranges from 20 to 56.

(5) *Supply Coy semi-trailer trucks* — This discrete factor represents the number of semi-trailer trucks in the supply company, able to transport one 40-foot container with a maximum weight of 25 tons. The range is from 5 to 18.

(6) *Supply Coy WOLF trucks* — This discrete factor represents the number of trucks of type WOLF in the supply company, which are used as a leading vehicle in a convoy, the range is between 5 and 14.

(7) *Supply Coy 5-ton trucks* — This discrete factor represents the number of 5-ton trucks within the supply company, the range is between 1 and 2.

(8) *Supply Coy drivers for DROPS trucks* — This discrete factor represents the number of drivers of the supply company who are trained to drive and operate the DROPS, their number ranges from 40 to 122.

(9) *Supply Coy drivers for semi-trailer trucks* — This discrete factor represents the number of drivers for operating the semi-trailer truck of the supply company, the range is from 10 to 36.

(10) *Supply Coy drivers for WOLF trucks* — This discrete factor represents the number of drivers for the WOLF within the supply company. The range is between 18 and 28.

(11) *Supply Coy drivers for 5-ton trucks* — This discrete factor represents the number of drivers for the 5-ton truck in the supply company, ranging from 2 to 4.

(12) *Supply Coy forklifts* — This discrete factor represents the number of forklifts in the supply company. It is used to transload boxes from and onto flatracks as well as in and out of containers. The range is from 5 to 20.

(13) *Supply Coy container-handling equipment* — This discrete factor represents the number of container-handling equipment used to transload containers onto trailers in the supply company, the range is between 2 and 6.

(14) *Supply Coy loading personnel* — This discrete factor represents the number the number of operating personnel of the forklifts and container-handling equipment of the supply company. Its range is from 25 to 40.

(15) *Transportation Coy planning personnel* — This discrete factor represents the number of personnel in the planning cell of the transportation company; the range is between 8 and 12.

(16) *Transportation Coy DROPS trucks* — This discrete factor represents the number of DROPS trucks within the transportation company, capable of carrying up to fourteen tons of supplies on flatracks. It ranges from 9 to 54.

(17) *Transportation Coy semi-trailer trucks* — This discrete factor represents the number of semi-trailer trucks in the transportation company, able to transport one 40-foot container with a maximum weight of 25 tons. The range is from 19 to 38.

(18) *Transportation Coy WOLF trucks* — This discrete factor represents the number of trucks of type WOLF in the transportation company, which is used as a leading vehicle in a convoy, the range is between 9 and 24.

(19) *Transportation Coy drivers for DROPS trucks* — This discrete factor represents the number of drivers of the transportation company who are trained to drive and operate the DROPS. Their number ranges from 18 to 118.

(20) *Transportation Coy drivers for semi-trailer trucks* — This discrete factor represents the number of drivers for operating the semi-trailer truck of the transportation company, the range is from 18 to 36.

(21) *Transportation Coy drivers for WOLF trucks* — This discrete factor represents the number of drivers for the WOLF within the transportation company. The range is between 18 and 48.

(22) *SPOD loading personnel* — This discrete factor represents the number the number of operating personnel of the forklifts and container-handling equipment of the transloading company at the SPOD. Its range is from 60 to 80.

(23) *SPOD forklifts* — This discrete factor represents the number of forklifts in the transloading company. It is used to transload boxes from and onto flatracks as well as in and out of containers. The range is from 4 to 20.

(24) *SPOD container-handling equipment* — This discrete factor represents the number of container-handling equipment used to transload containers onto trailers in the transloading company; the range is between 2 and 6.

(25) *Maintenance Coy 2-ton trucks* — This discrete factor represents the number of maintenance trucks within the maintenance company. One of these trucks accompanies each convoy. The range is between 9 and 18.

(26) *FP and MP Coy DINGO trucks* — This discrete factor represents the number of armored vehicle of type DINGO within the force protection and military police companies. Each convoy is accompanied by four of these vehicles, two from the MP and two from the FP company. The range is between 30 and 50.

(27) *Medical Coy FUCHS trucks* — This discrete factor represents the number of armored vehicle of type FUCHS of the medical company. One of these vehicles accompanies each convoy. Its range is from to 18.

(28) *MP Coy WOLF trucks* — This discrete factor represents the number of trucks of type WOLF in the MP company, which is used as a leading vehicle in a convoy; the range is between 18 and 36.

(29) *Water Convoy LOGBASE - SPOD - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the SPOD and back transporting water. The range is between 1 and 4.

(30) *Medical Convoy LOGBASE - SPOD - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the SPOD and back transporting medical supplies. The range is between 1 and 2.

(31) *Spares Convoy LOGBASE - SPOD - LOGBASE* — This discrete factor represents the maximum number of DROPS trucks that are used in a convoy from the LOGBASE to the SPOD and back transporting spare parts. The range is between 1 and 4.

(32) *Non-military Convoy LOGBASE - SPOD - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the SPOD and back transporting non-military supplies. The range is between 1 and 4.

(33) *Water Convoy LOGBASE - REC1 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 1 and back transporting water. The range is between 1 and 2.

(34) *Medical Convoy LOGBASE - REC1 - LOGBASE* — This discrete factor represents the maximum number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 1 and back transporting medical supplies. The range is between 1 and 2.

(35) *Non-military Convoy LOGBASE - REC1 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 1 and back transporting non-military supplies. The range is between 1 and 4.

(36) *Water Convoy LOGBASE - REC2 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 2 and back transporting water. The range is between 1 and 2.

(37) *Medical Convoy LOGBASE - REC2 - LOGBASE* — This discrete factor represents the maximum number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 2 and back transporting medical supplies. The range is between 1 and 2.

(38) *Non-military Convoy LOGBASE - REC2 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 2 and back transporting non-military supplies. The range is between 1 and 4.

(39) *Water Convoy LOGBASE - REC3 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 3 and back transporting water. The range is between 1 and 2.

(40) *Medical Convoy LOGBASE - REC3 - LOGBASE* — This discrete factor represents the maximum number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 3 and back transporting medical supplies. The range is between 1 and 2.

(41) *Non-military Convoy LOGBASE - REC3 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 3 and back transporting non-military supplies. The range is between 1 and 4.

(42) *Water Convoy LOGBASE - REC4 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 4 and back transporting water. The range is between 1 and 2.

(43) *Medical Convoy LOGBASE - REC4 - LOGBASE* — This discrete factor represents the maximum number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 4 and back transporting medical supplies. The range is between 1 and 2.

(44) *Non-military Convoy LOGBASE - REC4 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 4 and back transporting non-military supplies. The range is between 1 and 4.

(45) *Water Convoy LOGBASE - REC5 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 5 and back transporting water. The range is between 1 and 2.

(46) *Medical Convoy LOGBASE - REC5 - LOGBASE* — This discrete factor represents the number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 5 and back transporting medical supplies. The range is between 1 and 2.

(47) *Non-military Convoy LOGBASE - REC5 - LOGBASE* — This discrete factor represents the number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 5 and back transporting non-military supplies. The range is between 1 and 4.

(48) *Water Convoy LOGBASE - REC6 - LOGBASE* — This discrete factor represents the number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 6 and back transporting water. The range is between 1 and 2.

(49) *Medical Convoy LOGBASE - REC6 - LOGBASE* — This discrete factor represents the number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 6 and back transporting medical supplies. The range is between 1 and 2.

(50) *Non-military Convoy LOGBASE - REC6 - LOGBASE* — This discrete factor represents the number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 6 and back transporting non-military supplies. The range is between 1 and 4.

(51) *Water Convoy LOGBASE - REC7 - LOGBASE* — This discrete factor represents the number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 7 and back transporting water. The range is between 1 and 2.

(52) *Medical Convoy LOGBASE - REC7 - LOGBASE* — This discrete factor represents the number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 7 and back transporting medical supplies. The range is between 1 and 2.

(53) *Non-military Convoy LOGBASE - REC7 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 7 and back transporting non-military supplies. The range is between 1 and 4.

(54) *Water Convoy LOGBASE - REC8 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 8 and back transporting water. The range is between 1 and 2.

(55) *Medical Convoy LOGBASE - REC8 - LOGBASE* — This discrete factor represents the maximum number of DROPS trucks that are used in a convoy from the LOGBASE to the receiving point 8 and back transporting medical supplies. The range is between 1 and 2.

(56) *Non-military Convoy LOGBASE - REC8 - LOGBASE* — This discrete factor represents the maximum number of semi-trailer trucks that are used in a convoy from the LOGBASE to the receiving point 8 and back transporting non-military supplies. The range is between 1 and 4.

(57) *SPOD water uploading assets* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the SPOD; it ranges from 1 to 6.

(58) *SPOD medical uploading assets* — This discrete factor represents the number of container-handling devices used to upload containers with medical supplies onto the trailers at the SPOD; it ranges from 1 to 6.

(59) *SPOD spares uploading assets* — This discrete factor represents the number of forklifts used to upload flatracks with spare parts at the SPOD, it ranges from 1 to 6.

(60) *SPOD non-military uploading assets* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the SPOD; it ranges from 1 to 6.

(61) *LOGBASE water downloading assets* — This discrete factor represents the number of container-handling devices used to download containers with water from the trailers at the LOGBASE; it ranges from 1 to 6.

(62) *LOGBASE medical downloading assets* — This discrete factor represents the number of container-handling devices used to download containers with medical supplies from the trailers at the LOGBASE, it ranges from 1 to 6.

(63) *LOGBASE spares downloading assets* — This discrete factor represents the number of forklifts used to download spare parts from the flatracks at the LOGBASE, it ranges from 1 to 6.

(64) *LOGBASE non-military downloading assets* — This discrete factor represents the number of container-handling devices used to download containers with non-military supplies from the trailers at the LOGBASE, it ranges from 1 to 6.

(65) *LOGBASE water uploading assets for REC1* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 1; it ranges from 1 to 6.

(66) *LOGBASE medical uploading assets for REC1* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 1, it ranges from 1 to 6.

(67) *LOGBASE non-military uploading assets for REC1* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 1, it ranges from 1 to 6.

(68) *LOGBASE water uploading assets for REC2* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 2, it ranges from 1 to 6.

(69) *LOGBASE medical uploading assets for REC2* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 2, it ranges from 1 to 6.

(70) *LOGBASE non-military uploading assets for REC2* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 2, it ranges from 1 to 6.

(71) *LOGBASE water uploading assets for REC3* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 3; it ranges from 1 to 6.

(72) *LOGBASE medical uploading assets for REC3* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 3, it ranges from 1 to 6.

(73) *LOGBASE non-military uploading assets for REC3* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 3, it ranges from 1 to 6.

(74) *LOGBASE water uploading assets for REC4* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 4; it ranges from 1 to 6.

(75) *LOGBASE medical uploading assets for REC4* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 4, it ranges from 1 to 6.

(76) *LOGBASE non-military uploading assets for REC4* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 4, it ranges from 1 to 6.

(77) *LOGBASE water uploading assets for REC5* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 5; it ranges from 1 to 6.

(78) *LOGBASE medical uploading assets for REC5* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 5, it ranges from 1 to 6.

(79) *LOGBASE non-military uploading assets for REC5* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 5, it ranges from 1 to 6.

(80) *LOGBASE water uploading assets for REC6* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 6; it ranges from 1 to 6.

(81) *LOGBASE medical uploading assets for REC6* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 6, it ranges from 1 to 6.

(82) *LOGBASE non-military uploading assets for REC6* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 6, it ranges from 1 to 6.

(83) *LOGBASE water uploading assets for REC7* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 7; it ranges from 1 to 6.

(84) *LOGBASE medical uploading assets for REC7* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 7, it ranges from 1 to 6.

(85) *LOGBASE non-military uploading assets for REC7* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 7, it ranges from 1 to 6.

(86) *LOGBASE water uploading assets for REC8* — This discrete factor represents the number of container-handling devices used to upload containers with water onto the trailers at the LOGBASE with destination receiving point 8; it ranges from 1 to 6.

(87) *LOGBASE medical uploading assets for REC8* — This discrete factor represents the number of forklifts used to upload boxes with medical supplies onto the flatracks at the LOGBASE with destination receiving point 8, it ranges from 1 to 6.

(88) *LOGBASE non-military uploading assets for REC8* — This discrete factor represents the number of container-handling devices used to upload containers with non-military supplies onto the trailers at the LOGBASE with destination receiving point 8, it ranges from 1 to 6.

b. Noise Factors

(1) *Inhabitants of receiving point 1* — This discrete factor represents the number of inhabitants in the area around the receiving point 1. It ranges from 3,000 to 5,000.

(2) *Inhabitants of receiving point 2* — This discrete factor represents the number of inhabitants in the area around the receiving point 2. It ranges from 4,500 to 6,500.

(3) *Inhabitants of receiving point 3* — This discrete factor represents the number of inhabitants in the area around the receiving point 3. It ranges from 2,000 to 4,000.

(4) *Inhabitants of receiving point 4* — This discrete factor represents the number of inhabitants in the area around the receiving point 4. It ranges from 1,000 to 2,000.

(5) *Inhabitants of receiving point 5* — This discrete factor represents the number of inhabitants in the area around the receiving point 5. It ranges from 500 to 1,500.

(6) *Inhabitants of receiving point 6* — This discrete factor represents the number of inhabitants in the area around the receiving point 6. It ranges from 3,000 to 5,000.

(7) *Inhabitants of receiving point 7* — This discrete factor represents the number of inhabitants in the area around the receiving point 7. It ranges from 3,500 to 5,500.

(8) *Inhabitants of receiving point 8* — This discrete factor represents the number of inhabitants in the area around the receiving point 8. It ranges from 300 to 700.

(9) *Daily demand of water* — This continuous factor represents the daily demand of potable water per person per day in tons. The range is between 0.004 and 0.008.

(10) *Daily demand of medical supplies* — This continuous factor represents the daily demand of medical supplies per person per day in tons. The range is between 0.0001 and 0.0004.

(11) *Daily demand of spare parts* — This continuous factor represents the daily demand of spare parts per soldier per day in tons. The range is between 0.001 and 0.009.

(12) *Daily demand of non-military supplies* — This continuous factor represents the daily demand of non-military supplies per person per day in tons. The range is between 0.002 and 0.004.

(13) *REC1 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 1, ranging from 1 to 40.

(14) *REC1 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 1, it ranges from 1 to 10.

(15) *REC1 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 1, it ranges from 1 to 40.

(16) *REC2 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 2, ranging from 1 to 40.

(17) *REC2 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 2, it ranges from 1 to 10.

(18) *REC2 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 2, it ranges from 1 to 40.

(19) *REC3 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 3, ranging from 1 to 40.

(20) *REC3 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 3, it ranges from 1 to 10.

(21) *REC3 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 3, it ranges from 1 to 40.

(22) *REC4 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 4, ranging from 1 to 40.

(23) *REC4 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 4, it ranges from 1 to 10.

(24) *REC4 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 4, it ranges from 1 to 40.

(25) *REC5 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 5, ranging from 1 to 40.

(26) *REC5 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 5, it ranges from 1 to 10.

(27) *REC5 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 5, it ranges from 1 to 40.

(28) *REC6 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 6, ranging from 1 to 40.

(29) *REC6 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 6, it ranges from 1 to 10.

(30) *REC6 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 6, it ranges from 1 to 40.

(31) *REC7 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 7, ranging from 1 to 40.

(32) *REC7 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 7, it ranges from 1 to 10.

(33) *REC7 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 7, it ranges from 1 to 40.

(34) *REC8 water downloading assets* — This discrete factor represents the number of personnel unloading water from the convoy vehicles at receiving point 8, ranging from 1 to 20.

(35) *REC8 medical downloading assets* — This discrete factor represents the number of personnel unloading medical supplies from the convoy vehicles at receiving point 8, it ranges from 1 to 5.

(36) *REC8 non-military downloading assets* — This discrete factor represents the number of personnel unloading non-military equipment from the convoy vehicles at receiving point 8, it ranges from 1 to 5.

(37) *Probability short time "plan"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for planning purposes on brigade, battalion and company level, ranging from 0.10 to 1.00.

(38) *Probability short time "move to"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for the movements of the convoys. Distributions differ depending on the length of the route the convoy has to travel and additional rest times, ranging from 0.10 to 1.00.

(39) *Probability short time "form convoy"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for the actions of forming the different convoys. The times take into account acquiring the vehicles and drivers as well as the pre-drive checks and issuing the orders to the drivers, ranging from 0.10 to 1.00.

(40) *Probability short time "seize assets"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for the actions of making the supporting assets for loading and unloading of the convoys available. The times take into account acquiring the vehicles and drivers as well as issuing the orders to the personnel, ranging from 0.10 to 1.00.

(41) *Probability short time "upload"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for loading the convoy vehicles by forklifts, container-handling equipment and loading flatracks onto the DROPS, ranging from 0.10 to 1.00.

(42) *Probability short time "download"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for downloading the convoy vehicles by forklifts, container-handling equipment, downloading flatracks off the DROPS as well as downloading by hand at the receiving points, ranging from 0.10 to 1.00.

(43) *Probability short time "disband convoy"* — This continuous factor represents the probability that the time with an overall shorter triangular distribution will be used instead of an overall longer triangular distribution for disbanding the convoys. The times take post-drive checks, refueling and small repairs into account, ranging from 0.10 to 1.00.

2. Nearly Orthogonal Latin Hypercube (NOLH)

The design used in this research is a Nearly Orthogonal Latin Hypercube (NOLH), which provides a great advantage for the analysis. The NOLH designs are very flexible and efficient in use even with a high number of factors, such as in this research. This space-filling design throughout the experiment's region allows for the identification of linear and non-linear relationships among the factors as well as interactions, and also allows greater details over the whole range of the factors in contrast to designs where, for example, just the lower and the upper level of the factor ranges are taken into account. A nearly orthogonal design is characterized by low correlation between all pairs of factors, making it easier to separate the impacts of different terms in the model. In addition, the NOLH design factors can easily be removed or added, and the levels of these factors can be changed just as easily. These facts provide closer insights into the response surface (Kleijnen et al., 2005; Sanchez, 2006).

The NOLH design used in this research was constructed by Professor Susan Sanchez. It is based on the approach for continuous-valued factors of Cioppa and Lucas (2007) and Hernandez (2008), but modified to accommodate the large number of discrete factors. Out of the total 131 quantitative factors, eleven were continuous, 52 were discrete with ten up to 2,001 levels (and handled as continuous), but 68 were discrete with two up to 7 levels. The last category means that a design based on rounding the levels for a continuous-factor design results in large pairwise correlations unless the number of design points is large. This is not a problem for quick-running simulations, but test runs of the first 240 hrs of the scenario indicated that the LBC model could take a long time to complete. A design with 324 design points yields a maximum pairwise correlation beneath five percent.

C. CONDUCTING THE SIMULATION

1. LBC Model Input File Creation

As described in Chapter II, the LBC model requires input files either in the .xls, .xlsm or .xml file format. Every design point represents a single input file for the model. Therefore, this research needs 324 separate input files. Because the current version of the LBC model does not support the implementation of the DOE, visual basic for applications (VBA) code was created to generate the input files automatically for every design point.

This VBA code reads the level settings of every factor of a design point, fills in the value in the appropriate sheets and cells of the input file, and saves the input file with its distinct file name. This process repeats for every design point. After creating every single input file as a .xlsm file, the .xlsm files were converted into .xml files using the LBC model's conversion capability. Using a Macintosh laptop running Windows XP with a 2.4 GHz processor and 2 GB RAM it took about fourteen minutes to create the 324 input files and another sixty minutes to convert them.

2. Terminating the Simulations

The initial state of all simulations is that all receiving points and the LOGBASE are fully topped off with all commodities and no convoys are traveling. All resources are idle. The simulation is terminated after a simulation run time of 9,600 hours, which is equivalent to 400 days.

3. Computing Resources

The analysis of this stochastic simulation process requires multiple runs for every design point. LBC is capable of running on a stand-alone computer, but to use time more effectively, production runs can be made on a computer cluster. The cluster used is NPS's Reaper with fifty-two nodes. Stephen C. Upton, research associate of the SEED Center at NPS, assisted the author of this research in conducting the production runs. Ten replications were planned initially, but the analysis in Chapter V involves only three runs on each of the 324 design points. The time to complete each depended on the factor setting; some design points were complete in ten minutes, while others took four days to complete. Due to the large amount of memory required, some runs could not be completed using Reaper (even with three replications) and had to be conducted on TRAC's Alien machine with 12GB RAM. This is discussed further in Chapter V, Section C.

V. ANALYSIS

A. METHODOLOGY, TOOLS AND TECHNIQUES

1. Methodology

After completing the simulation runs, different tools and techniques were used to manipulate and clean the output files and to investigate the impact of the factors on the MOE. Graphical analysis techniques were used, as were multiple regression and classification and regression trees, to gain insight into the underlying structure of the scenario, extract the important factors and detect outliers and their impact on the analysis. As discussed later in this chapter, this analysis uncovered additional limitations of the LBC model and problems with its execution that could not be resolved. Some of these may relate to characteristics of the scenario, but others are more general. Consequently, while this chapter contains an overview of some key analysis methodologies that would be appropriate for analyzing the results of a large-scale experiment for the LBC model or another computational model, the reader should be cautioned that the results are for illustrative purposes only.

2. File Concatenation Tool

The LBC model creates separate output files for each design point. A Java-based tool, designed by Mrs. Jane Wu from TRAC MTRY, made it possible to concatenate the output files from all the design points, and then add the associated design point information into the file.

3. Data Cleaning Tool

The concatenated output files with the DOE had to be further cleaned in order to do analysis with JMP (e.g., duplicate lines in the files had to be removed, unwanted columns had to be removed, etc.) Due to a large number of lines in the output files of the LBC model with single file sizes up to 4.5 GB, Microsoft Excel and JMP could not be used to clean the data due to the upper limit of rows in

Microsoft Excel or the restriction on memory in JMP. The IBM SPSS PASW Modeler 13 software package, which is designed to handle large data sets, was used to clean the data and reduce the size of the files (IBM SPSS, 2010). The streams built to clean the data are shown in Figure 8.

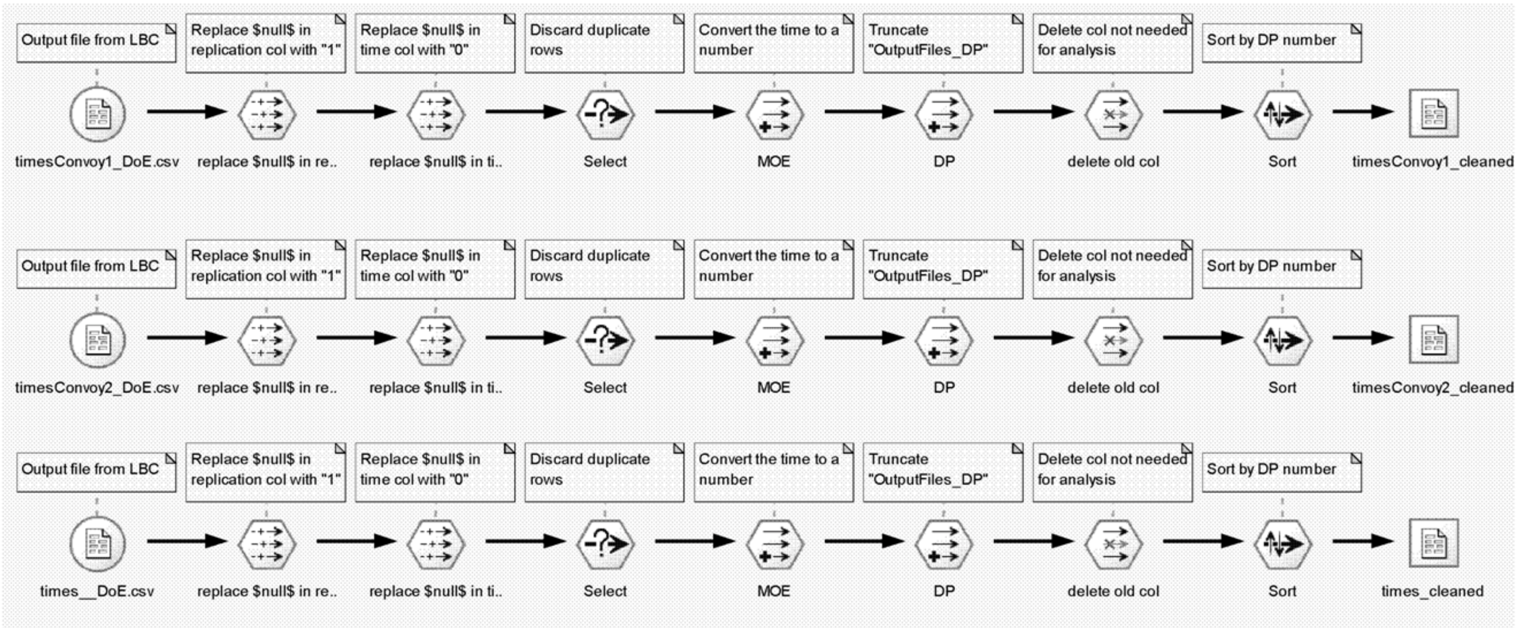


Figure 8. Streams in PASW Modeler 13

4. Analysis Tool

JMP Statistical Discovery Software, a product of SAS, is used as the statistical software package to conduct the analysis of the data collected from the output files of the LBC model. JMP's visualization capabilities allow us to conduct graphical analysis, fit multiple regression models, and construct classification and regression trees. Together with the capability of handling relatively large data files, this allows us to investigate the data and understand the analysis with just one tool.

5. Analysis Techniques

The analysis of the data focuses on the techniques to examine and understand the scenario, explore the data sets, and detect a structure in the relationships between the factors and the responses. This analysis makes use of three different techniques: graphical analysis, multiple regression, and classification and regression trees. These techniques are used in a complimentary manner in order to help to answer the research questions. In the following paragraphs, each technique will be described briefly.

a. Graphical Analysis

Graphics are a fundamental part of analysis. They are used in the initial data exploration and help communicate information by visualization. Graphical tools used in this research are scatter plots, histograms, and leverage plots. Analyses using these graphical tools provide the means to gain insight into the data set for factor selection, outlier detection, factor effect determination, and statistical model validation. Furthermore, these tools strengthen the research results by visualization.

b. Multiple Regression

Multiple linear regression allows the analyst to examine the impact of many factors on the MOE simultaneously. The objective is to learn more about the factors' effects and about the relationship between the factors and the MOEs. In the end, multiple linear regression shows which terms (i.e., main effects for the factors, as well as interactions and quadratic effects) the biggest impact on the different MOEs. Furthermore, the fitted regression model is a detailed description of the simulation model's behavior that may suggest factor combinations of interest that were not been examined in the initial DOE (Kleijnen et al., 2005).

c. Classification and Regression Trees

Using classification and regression trees is another way to analyze data without using methods that focus on equations. This technique makes use of rules that recursively split a data set into homogeneous subsets with the relationship between the response variable and the predictors. Each split looks a step ahead to see where the best possible spilt will be, by considering all possible splits given the current tree. The best possible split is considered the one with the partition of the largest likelihood ratio chi-squared statistic (Gaudard et al., 2006).

"The basic purpose of a classification study can be either to produce an accurate classifier or to uncover the predictive structure of the problem" (Breiman et al., 1984, p. 6). In this study, the purpose is to uncover the predictive structure, i.e., the importance of the factors for a prediction of the MOE. Breiman and the co-authors discuss several different methods to find out what the best split may be (Breiman et al., 1984). Numerous other methods have been developed in the past years, but there is no single "best" method.

Multiple regression and regression trees have different strengths. Multiple regression is good for fitting smooth responses, while regression trees may fit better if there are distinct thresholds or clusters in the response. By using different methods and comparing the results, the analyst may receive confirmation about which factors are most influential if the results reinforce each other. Or, if they differ, this may help the analyst pull out the interesting features of the data.

B. MEASURE OF EFFECTIVENESS

1. MOE 1: Time of Convoy 1 (LOGBASE - SPOD - LOGBASE)

For this MOE, only 68 design points showed results. That implies that in just these 68 experiments the convoy traveled from the LOGBASE to the SPOD and back to the LOGBASE. Before looking closely at the MOE 2 values, we construct an indicator for whether or not results were obtained. The regression tree in Figure 9 shows the first two splits with a resulting R^2 value of 0.46; the most important factors are the container handling equipment located at the LOGBASE (SC_HYSTER), and the SPOD (SPOD_HYSTER) used to transload all containers at these locations. The critical number, in determining whether a convoy can be loaded (and therefore can travel), is four for the supply company at the LOGBASE and four as well for the transloading company at the SPOD. The blue bars in the graph depict design points where convoys were traveling.

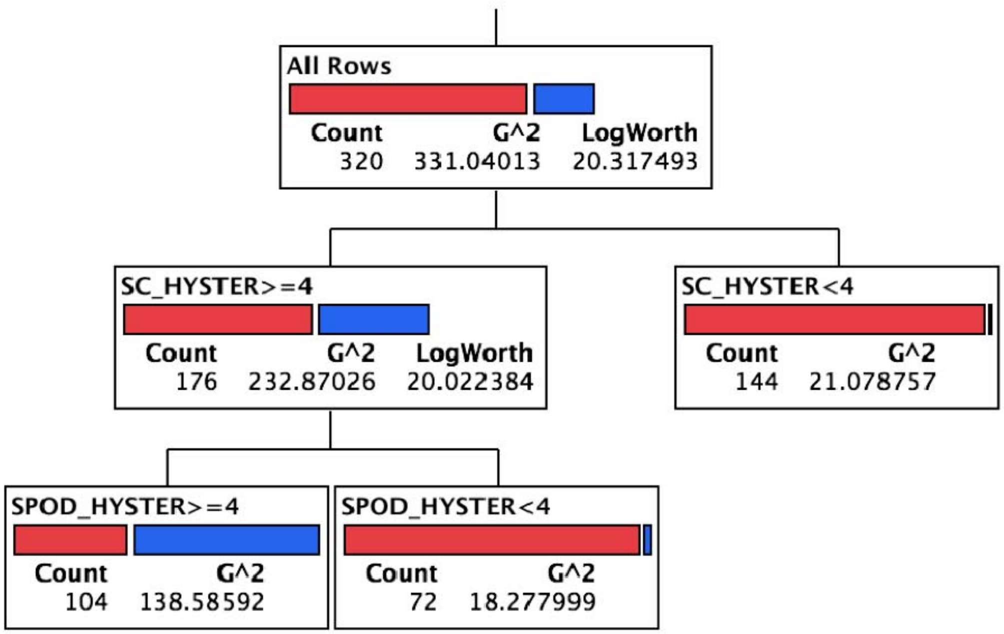
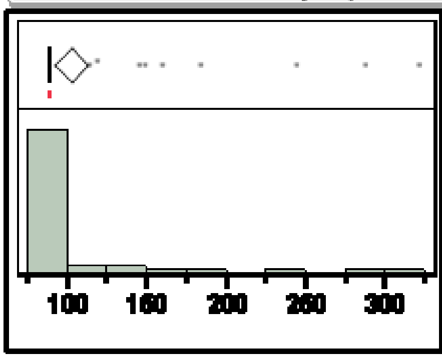


Figure 9. Regression Tree for the Indicator whether Convoys 1 were traveling or not

The distribution and summary statistics for the mean time of the convoy traveling from the LOGBASE to the SPOD and returning back to the LOGBASE (for all design points where these convoys actually took place) is shown in Figure 10. The distribution of the mean for the convoy is highly skewed with a mean of 102.31 hours, a 95% confidence interval for this mean ranging from 91.74 to 112.87 hours, a minimum of 86.88 hours, and a maximum of 321.42 hours.

Mean time for Convoy 1 (LOGBASE - SPOD - LOGBASE)



Quantiles

100.0%	maximum	321.42
99.5%		321.42
97.5%		298.72
90.0%		146.81
75.0%	quartile	90.84
50.0%	median	88.95
25.0%	quartile	88.42
10.0%		87.69
2.5%		87.05
0.5%		86.88
0.0%	minimum	86.88

Moments

Mean	102.30686
Std Dev	43.831648
Std Err Mean	5.2911023
Upper 95% Mean	112.86893
Lower 95% Mean	91.744781
N	69

Figure 10. Distribution and Summary Statistics for the Mean Time of the Convoy from the LOGBASE to SPOD to LOGBASE

Figure 11 shows the regression tree for the mean time of the convoy from the LOGBASE to the SPOD and back to the LOGBASE, given that one or more convoys completed a round trip. The tree consists of three splits and then achieves an R^2 value of 0.455; that value cannot be increased by further splits. The most important factors in the tree are at split one: the probability that the time for forming a convoy (i.e., giving orders to the company, acquiring the trucks and drivers, giving orders to the drivers and driving to the loading area) will be short. Split two says the loading assets for medical supplies (e.g., forklifts) for REC7 have an impact on the mean time of the convoy. That can be explained by the fact that all loading and unloading assets are being used for the convoy LOGBASE - SPOD - LOGBASE, as well as for the convoys that distribute supplies from the LOGBASE to the receiving points. In the last split, the number of inhabitants of REC3, which drive the amount of supplies that will be delivered, is not explanatory for the convoy traveling time. This number has, in practice, no influence on that time, meaning in real world the number of inhabitants of one of the eight receiving points would have no influence on the travel time. The influence in this model results from the demand of commodities at that point, the number of inhabitants of this point, the resulting number of transportation and transloading assets used to re-supply this receiving point and therefore reduces the number of available assets needed for the convoy going to an from the SPOD.

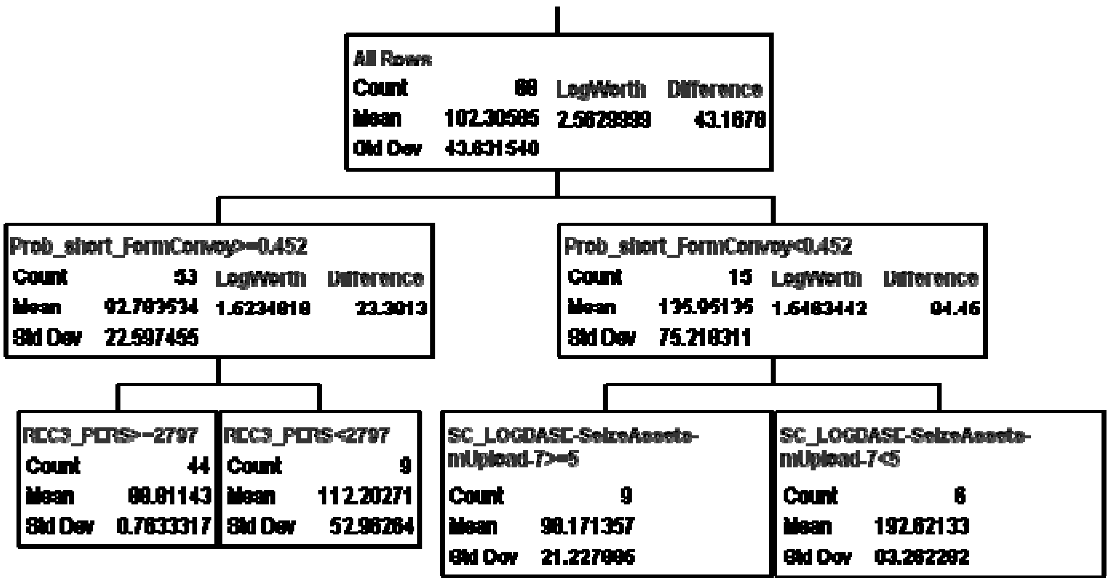
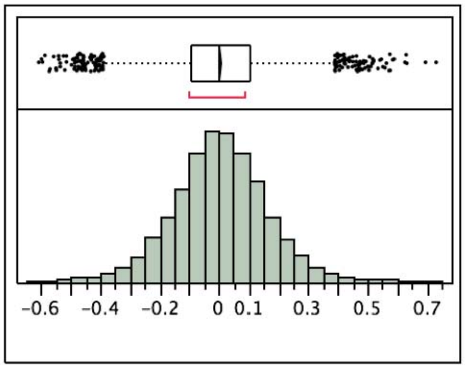


Figure 11. Regression Tree for the Mean Time of the Convoy from the LOGBASE to SPOD to LOGBASE

As stated in Chapter IV, using a nearly orthogonal experimental design has mathematical benefits for estimating the model effects. However, although the full design is nearly orthogonal, this is not true when we look at the set of design points that yield results for this MOE. The pairwise correlation analysis results in a large number of pairwise correlations with high magnitudes. Figure 12 shows the distribution and summary statistics of the pairwise correlation over all 68 design points with results, while Figure 13 shows the same but for the absolute value of the pairwise correlation. The range is from 0 to a maximum of

0.73 with a mean of 0.12. The maximum pairwise correlation occurs between the factors of the container handling equipment at the SPOD and the LOGBASE respectively.

Correlation



Quantiles

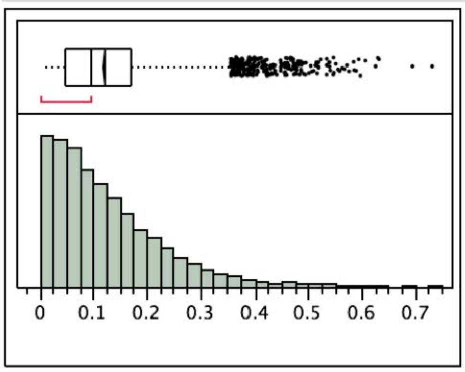
100.0%	maximum	0.73263
99.5%		0.46416
97.5%		0.3154
90.0%		0.19422
75.0%	quartile	0.09913
50.0%	median	0.00156
25.0%	quartile	−0.0937
10.0%		−0.1908
2.5%		−0.3117
0.5%		−0.4577
0.0%	minimum	−0.6078

Moments

Mean	0.0020427
Std Dev	0.1563818
Std Err Mean	0.0016947
Upper 95% Mean	0.0053647
Lower 95% Mean	−0.001279
N	8515

Figure 12. Distribution and Summary Statistics for the Factor Pairwise Correlations for Design Points yielding MOE 2 results

absolute value of correlation



Quantiles

100.0%	maximum	0.73263
99.5%		0.50633
97.5%		0.3739
90.0%		0.25624
75.0%	quartile	0.16958
50.0%	median	0.09636
25.0%	quartile	0.04468
10.0%		0.01767
2.5%		0.00385
0.5%		0.00089
0.0%	minimum	0

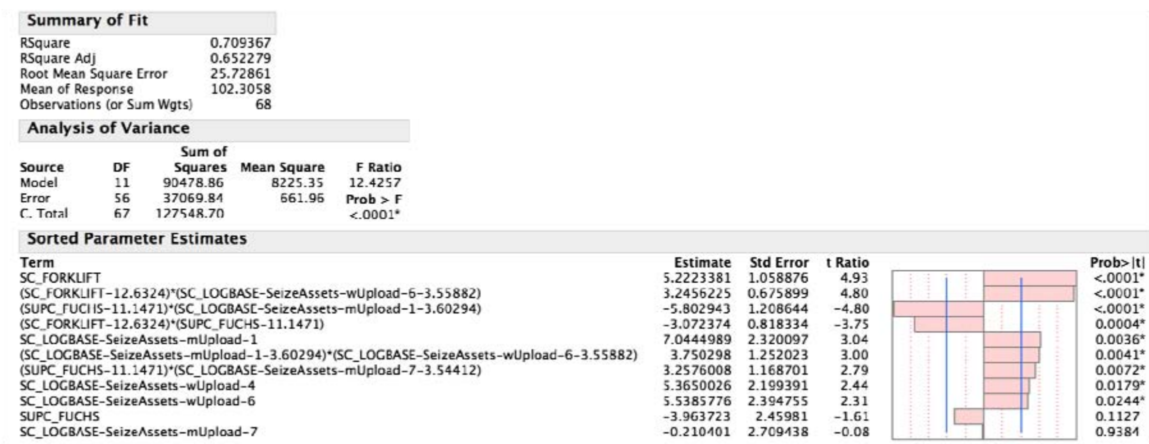
Moments

Mean	0.1204789
Std Dev	0.0997125
Std Err Mean	0.0010806
Upper 95% Mean	0.1225971
Lower 95% Mean	0.1183607
N	8515

Figure 13. Distribution and Summary Statistics for the Factor Absolute Value Pairwise Correlations for Design Points yielding MOE 2 results

The existence of high pairwise correlations is an example of multicollinearity. This causes problems for model fitting, because the estimate of a particular effect varies based on the other terms included in the model. Multicollinearity can artificially inflate the estimated variances of the model coefficients and, in severe cases, even lead to incorrect signs on the coefficients (Ryan, 1997).

We built a stepwise regression model for the mean time of the convoy from the LOGBASE to the SPOD and back to the LOGBASE. We adapted this interactively by evaluating the terms for statistical and also practical significance. Adding quadratic effects for the terms did not improve the model, but by including two-way interaction terms, we were able to get a good fit. The final regression model (Figure 14) achieves a R^2 value of 0.71. The most important factors are the number of a convoy accompanying vehicles from the medical company, and all loading and unloading assets. The strongest effects involve the total number of forklifts, and including the container handling equipment used for each convoy.



Summary of Fit

RSquare	0.709367
RSquare Adj	0.652279
Root Mean Square Error	25.72861
Mean of Response	102.3058
Observations (or Sum Wgts)	68

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	90478.86	8225.35	12.4257
Error	56	37069.84	661.96	Prob > F
C. Total	67	127548.70		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
SC_FORKLIFT	5.2223381	1.058876	4.93	<.0001*
(SC_FORKLIFT-12.6324)*(SC_LOGBASE-SeizeAssets-wUpload-6-3.55882)	3.2456225	0.675899	4.80	<.0001*
(SUPC_FUCHS-11.1471)*(SC_LOGBASE-SeizeAssets-mUpload-1-3.60294)	-5.802943	1.208644	-4.80	<.0001*
(SC_FORKLIFT-12.6324)*(SUPC_FUCHS-11.1471)	-3.072374	0.818334	-3.75	0.0004*
SC_LOGBASE-SeizeAssets-mUpload-1	7.0444989	2.320097	3.04	0.0036*
(SC_LOGBASE-SeizeAssets-mUpload-1-3.60294)*(SC_LOGBASE-SeizeAssets-wUpload-6-3.55882)	3.750298	1.252023	3.00	0.0041*
(SUPC_FUCHS-11.1471)*(SC_LOGBASE-SeizeAssets-mUpload-7-3.54412)	3.2576008	1.168701	2.79	0.0072*
SC_LOGBASE-SeizeAssets-wUpload-4	5.3650026	2.199391	2.44	0.0179*
SC_LOGBASE-SeizeAssets-wUpload-6	5.5385776	2.394755	2.31	0.0244*
SUPC_FUCHS	-3.963723	2.45981	-1.61	0.1127
SC_LOGBASE-SeizeAssets-mUpload-7	-0.210401	2.709438	-0.08	0.9384

Figure 14. Regression Model for the Mean Time of the Convoy from the LOGBASE to SPOD to LOGBASE

2. MOE 2: Time for Convoy 2 (LOGBASE - Receiving Points - LOGBASE)

For the mean time for convoy 2, results were observed from 90 experiments, i.e., only in 90 experiments did these convoys actually distribute supplies to any receiving point. In all those runs, they resupplied all eight receiving points. With an R^2 value of 0.19, the driving factor that determines whether any convoys will travel is the amount of container-handling equipment at the supply company at the LOGBASE.

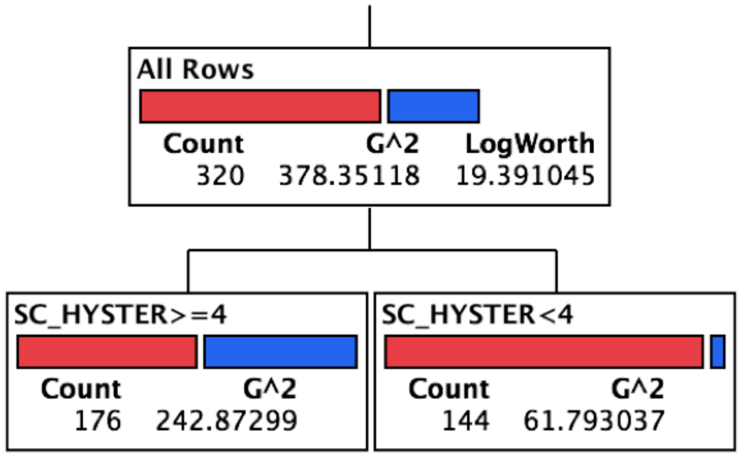
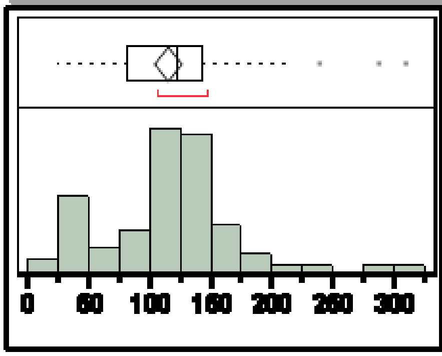


Figure 15. Regression Tree for the Indicator whether Convoys 2 were Traveling or not

The distribution and the summary statistics of the mean time for the convoys operating between the LOGBASE and the receiving points are shown in Figure 16. The mean time is 115.15 hours over all the different routes of the convoys, although this number is difficult to interpret given the censoring in the data. The distribution has a minimum of 22.78 hours and a maximum of 309.42 hours. This large range can be explained in part by the wide spread of distances from the LOGBASE to each of the eight receiving points. The total travel time, without loading and unloading, was anticipated to be between 3.4 and 10.3 hours, calculated by the distance (see Table 1) and the fixed average speed of a convoy. The resulting numbers from the experiments are larger in part because of the long loading and unloading times, but the maximum values indicate severe problems that should not occur in practice.

Mean time for Convoy 2 (LOGBASE - REC - LOGBASE)



Quantiles

100.0%	maximum	309.42
99.5%		309.42
97.5%		273.71
90.0%		183.83
75.0%	quartile	142.10
50.0%	median	121.92
25.0%	quartile	82.22
10.0%		37.04
2.5%		26.16
0.5%		22.78
0.0%	minimum	22.78

Moments

Mean	116.16467
Std Dev	58.279603
Std Err Mean	6.1432612
Upper 95% Mean	128.37061
Lower 95% Mean	103.95873
N	90

Figure 16. Distribution and Summary Statistics for the Mean Time of the Convoys from the LOGBASE to REC to LOGBASE

The regression tree built for this MOE is shown in Figure 17. As all factors related to the SPOD have no practical influence on this MOE, they are omitted as factors for the regression tree. After five splits, the R^2 value results in 0.51. Splitting further does not lead to any practical improvement. The first two splits are related to the number of transloading assets, while the last three splits are associated with the number of trucks and drivers. The round-trip travel time is lower if more assets are available.

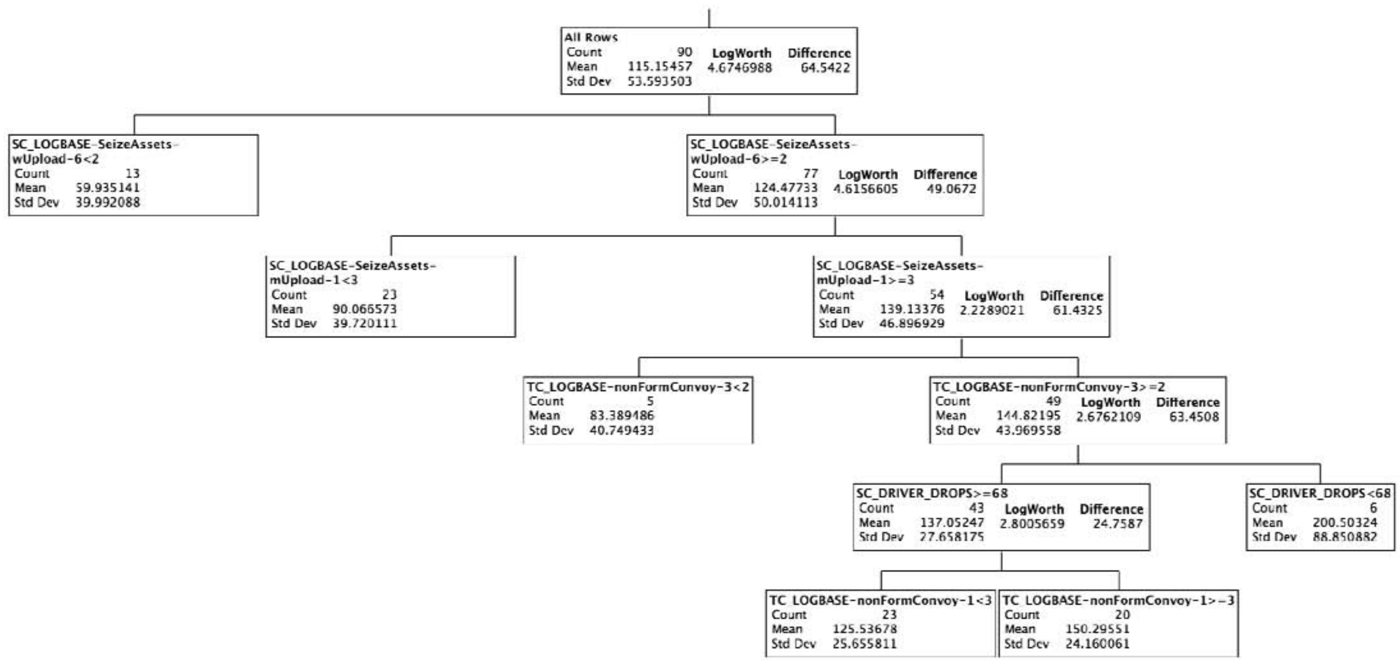


Figure 17. Regression Tree for the Mean Time of the Convoys from the LOGBASE to REC to LOGBASE

As done with the previous MOE, the pairwise correlations among factors were checked for the 90 design points yielding results. The minimum of the absolute pairwise correlation is practically 0, the maximum is 0.45 and the mean is 0.09 as shown in Figures 18 and 19.

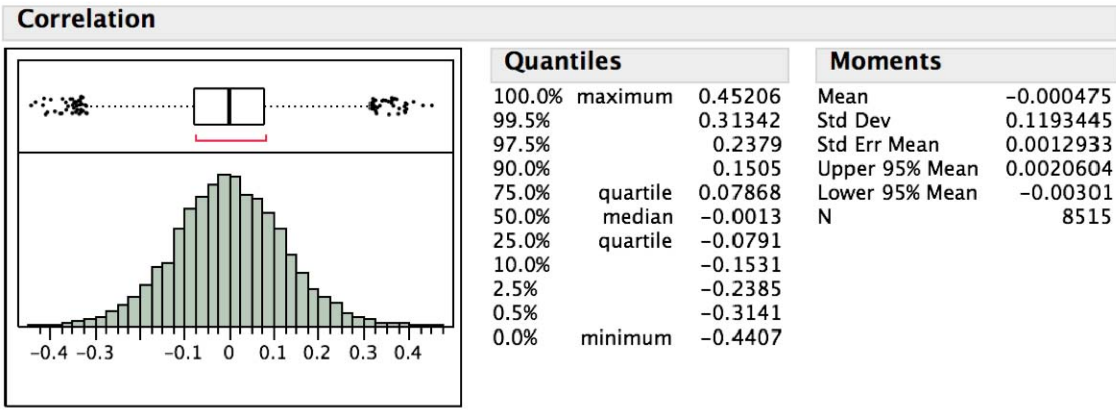


Figure 18. Distribution and Summary Statistics for the Factor Pairwise Correlations for Design Points yielding MOE 3 results

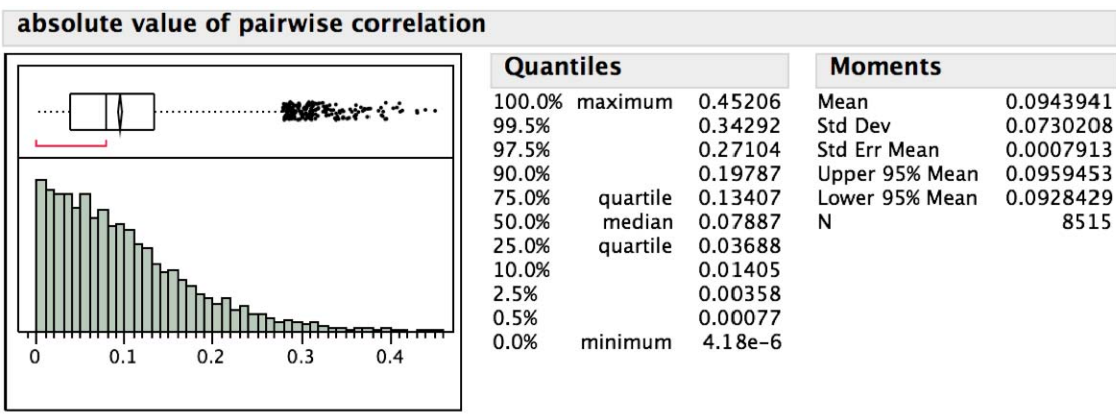


Figure 19. Distribution and Summary Statistics for the Factor Absolute Value Pairwise Correlations for Design Points yielding MOE 3 results

Following the same path for building the regression model, first a stepwise regression was built. The most significant factors were then used to build a regression model without interaction terms. That model yielded an R^2 value of 0.766. Introducing quadratic effects to the model yielded no improvement, but adding two-way interaction terms and eliminating factors that were not practically significant factors resulted in a R^2 value of 0.842. As that model had 63 non-significant terms a stepwise regression was built from that model resulting in the final model shown in Figure 20 with an R^2 value of 0.56. As the most important factors, the total number of the container handling equipment and the transloading equipment (i.e., forklifts and container-handling equipment) are included the model. Here as well, the container handling equipment is the driving factor for the convoy round-trip completion times.

Summary of Fit

RSquare	0.559583
RSquare Adj	0.496666
Root Mean Square Error	38.23689
Mean of Response	115.1955
Observations (or Sum Wgts)	89

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	143039.45	13003.6	8.8940
Error	77	112578.60	1462.1	Prob > F
C. Total	88	255618.06		<.0001*

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
SC_HYSTER	-28.34958	4.797055	-5.91	<.0001*
(SC_HYSTER-4.66292)*(SPOD-SeizeAssets-sUpload-1-3.2809)	-12.28756	2.486647	-4.94	<.0001*
SPOD-SeizeAssets-sUpload-1	11.830488	3.064988	3.86	0.0002*
(TC_LOGBASE-mFormConvoy-5-1.59551)*(SPOD-SeizeAssets-sUpload-1-3.2809)	-21.38143	5.77138	-3.70	0.0004*
(SC_LOGBASE-SeizeAssets-mUpload-1-3.4382)*(SC_LOGBASE-SeizeAssets-wUpload-6-3.5618)	4.3130259	1.276689	3.38	0.0011*
SC_LOGBASE-SeizeAssets-wUpload-6	7.434464	2.523005	2.95	0.0042*
SC_LOGBASE-SeizeAssets-mUpload-1	7.5015068	2.582986	2.90	0.0048*
(SC_SEMI-11.618)*(SC_LOGBASE-SeizeAssets-wUpload-2-3.65169)	-1.801563	0.852494	-2.11	0.0378*
TC_LOGBASE-mFormConvoy-5	18.659787	8.961856	2.08	0.0407*
SC_LOGBASE-SeizeAssets-wUpload-2	-4.785428	2.57004	-1.86	0.0664
SC_SEMI	-2.581877	1.717863	-1.50	0.1369

Figure 20. Regression Model for the Mean Time of the Convoys from the LOGBASE to REC to LOGBASE

3. Comparison of the Convoy Time MOEs

The models for MOE 1 and MOE 2 are simple enough to be compared directly, but this is not always the case when there are multiple performance measures and many important terms. One way to compare MOE 1 and 2 is to assess the importance of different factor categories (from Table 3) and the distinction between decision and noise factors, rather than the importance of individual factors. The number given in Table 4 depicts the R^2 value of the logistic regression with the indicator whether an experiment yielded observations or not as the response variable, except for the last row where the values from final model of the former analysis is shown. This table could be expanded for additional MOEs.

	MOE 1	MOE 2
Force Structure	0.19	0.26
Demand	0.02	0.02
Convoy	0.08	0.07
Transloading assets	0.09	0.08
Probabilities	0.01	0.01
All factors	0.35	0.47
All decision factors	0.28	0.39
All noise factors	0.06	0.06
Final model (incl. interactions)	0.71 (9 terms)	0.56 (9 terms)

Table 4. Comparison of MOEs 1 and 2 According to the Categories and Decision/Noise Factors (Numbers depict the R^2 values of the logistic regression on the indicator)

For MOE 1 and 2, the group that has most impact among all groups is "Force Structure." Here, the total number of available transloading and transportation assets are set.

The analysis of MOE 1 and 2 was done in two steps: the first step analyzed which factor was most important for a convoy traveling at all, and the second step analyzed which factors have the most impact, given convoys were generated by the LBC model. In both instances, it appears that the container-handling equipment is the driving factor. Assuring a high availability of this type of transloading equipment will improve the outcome of the whole operation.

However, the reader is cautioned against relying on the results of these analyses, given the censoring problems with the LBC model. The following table shows an overview of the number of design points where convoy 1, convoys 2, and both were generated.

number of DP with convoy 1	number of DP with convoy 2	number of DP with both convoy 1 and 2
68	90	67

Table 5. Number of Design Points with Convoys Traveling

4. MOE 3: Delivery of Commodities

Generating convoys was a problem throughout all the experiments conducted for this research. Because of the large number of design points where convoys were not generated, we provide descriptive statistics of this MOE, rather than fitting models. Although all experiments were completed with three replications, convoys were not generated for the whole 9,600 hours of simulation time. To investigate why convoys stopped being formed, a design point where many convoys traveled was chosen and observed more closely. Design point 104 had, in total, 29 convoys traveling from the LOGBASE to the eight receiving points. Table 6 shows the destination, the approximate time of arrival in hours of simulation time, as well as the commodities the convoy transported. Each commodity was transported by its assigned transportation vehicle, i.e., water and non-military supplies in a container and medical supplies by a truck of type DROPS, and all trucks were fully loaded with 25 and 14 tons of supplies respectively.

REC	approx. time of arrival of convoy (in hours)	commodities		
		water	medical	non-mil.
1	25	x	x	x
2	48	x	x	x
	136	x	x	x
	308	x	x	x
	465	x		x
3	40	x	x	x
	157	x	x	x
	299	x		x
	488	x		x
4	64	x	x	x
	175	x	x	x
	332	x	x	x
	510	x		x
5	82	x	x	x
	200	x	x	x
	580	x		x
6	78	x	x	x
	198	x	x	x
	340	x	x	x
	534	x		x
7	20	x	x	x
	107	x	x	x
	224	x	x	x
	389	x		x
	695	x		x
8	82	x	x	x
	197	x	x	x
	352	x		x
	562	x		x

Table 6. Overview of the Convoy Arrival Times and Transported Commodities of Design Point 104.

Table 7 depicts more details on these convoys. Green (shaded) cells in this table show the arrival of the specified commodity at the receiving point, whereas white cells show at what time the stock level of that commodity reached zero. From these times, the total amounts of time where the receiving points were without stock were calculated. The numbers given in the last row show the percentage of time without any supplies over the whole 9,600 hours of simulated time. As expected, with no more convoys traveling beyond hour 695, this number is very high and, in practice, completely unacceptable. Why the simulation stopped generating convoys cannot be determined from this analysis. In order to see where the LBC model has its problems, an alternate model, e.g. built with the Arena software package, should be used in further research to see if it is an issue with the LBC model.

Receiving Point	REC1			REC2			REC3			REC4		
Commodity	water	medical	non-mil.	water	medical	non-mil.	water	medical	non-mil.	water	medical	non-mil.
Times of Resupply (green) or Times where Stock Level is Zero	25.57	25.15	25.76	48.00	24.00	47.67	40.75	24.00	24.00	48.00	24.00	24.00
	96.00	576.00	96.00	48.48	47.31	72.00	72.00	40.17	41.19	64.40	64.28	64.93
				72.00	134.19	136.68	157.31	155.05	72.00	120.00	178.13	168.00
				136.35	307.51	168.00	192.00	485.78	158.42	179.41	331.91	180.22
				144.00	840.00	308.78	299.07	1392.00	192.00	240.00	510.18	288.00
				307.79		336.00	336.00		298.57	334.31	3648.00	334.28
				312.00		465.80	488.29		336.00	384.00		432.00
				465.99		504.00	528.00		487.96	512.41		510.95
				480.00					528.00	576.00		624.00
Hours without Supply 1)	0.00	0.00	0.00	382.61	0.00	121.07	142.58	0.00	362.14	298.53	0.00	178.38
Percentage without Supply 1)	0.0%	0.0%	0.0%	79.7%	0.0%	24.0%	27.0%	0.0%	68.6%	51.8%	0.0%	28.6%
Hours without Supply 2)	9504.00	9024.00	9504.00	9502.61	8760.00	9217.07	9214.58	8208.00	9434.14	9322.53	5952.00	9154.38
Percentage without Supply 2)	99.0%	94.0%	99.0%	99.0%	91.3%	96.0%	96.0%	85.5%	98.3%	97.1%	62.0%	95.4%

Receiving Point	REC5			REC6			REC7			REC8		
Commodity	water	medical	non-mil.	water	medical	non-mil.	water	medical	non-mil.	water	medical	non-mil.
Times of Resupply (green) or Times where Stock Level is Zero	48	48	48	48	48	48	21.54	18.85	20.59	48	48	48
	82.4	81.41	84.4	78.3	77.25	79.53	72	105.91	72	82.44	81.22	82.78
	200.16	198.83	201.06	120	198.09	144	108.29	224.31	107.71	197.27	195.81	198.48
	365.56	4656	366.33	198.92	339.36	198.62	144	1080	144	353.11	9384	352.84
	581.84		581.03	240	1536	264	224.45		224.57	562.22		561.79
	768		1032	340.54		341.4	264		264	1464		1992
				384		408	389.8		389.99			
				534.22		534.73	432		432			
				576		600	695.32		694.67			
							720		720			
Hours without Supply 1)	0	0	0	359.98	0	290.28	505.86	0	504.94	0	0	0
Percentage without Supply 1)	0.0%	0.0%	0.0%	62.5%	0.0%	48.4%	70.3%	0.0%	70.1%	0.0%	0.0%	0.0%
Hours without Supply 2)	8832	4944	8568	9383.98	8064	9290.28	9385.86	8520	9384.94	8136	216	7608
Percentage without Supply 2)	92.0%	51.5%	89.3%	97.7%	84.0%	96.8%	97.8%	88.8%	97.8%	84.8%	2.3%	79.3%

: Arrival of convoy with resupply
1) : Based on the time when the last convoy arrives at the receiving point
2) : Based on 9600 hours of simulation time

Table 7. Detailed List of all Convoys in Design Point 104 with Summary

C. LESSONS LEARNED FROM THE LBC MODEL

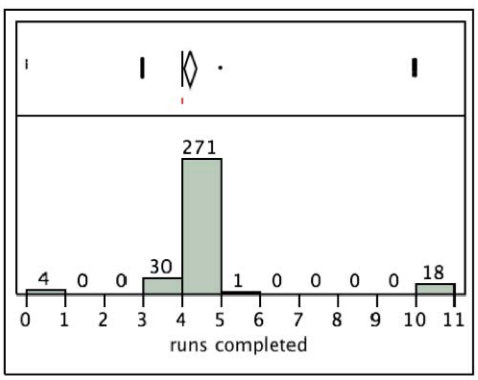
During this research, we uncovered some shortcomings of the LBC model that were not obvious beforehand. That is because of the limited use of the model. The dynamic maintenance part of the model was used in thesis research in December 2006 where the focus was on the impact of varying levels of reliability on future combat systems maintenance requirements (Dozier, 2006), in an OSD update for the Future Combat System (FCS) for fiscal year 2007, and for an evaluation of alternatives for the Joint Light Tactical Vehicle (JLTV) in the year 2008. The LBC model was used in thesis research in 2008 (Baez, 2008) with the focus on the second phase of the capability-based assessment (CBA) process. LBC was used as part of the functional solutions analysis during the third phase of the CBA process, conducted at TRADOC MONTEREY in 2008. It was also used in a study of alternatives for the distribution of water, petroleum and lubricants conducted by Advanced Concepts and Technologies International (ACT I) sponsored by the Quartermaster Center and School in December 2008 (TRADOC MONTEREY, 2010). The latest uses of the LBC model include a study of choices for the dynamic maintenance of various platforms conducted by TRAC from April 2008 to June 2009, a study of the Ground Combat Vehicle Analysis of Alternatives from October 2009 to present led by TRAC, and finally a study of the Logistics Sustainment to Joint Distributions Operations from February 2010 to present led by the Joint Forces Command.

To the best of our knowledge, the LBC model has not been used for studies other than those mentioned above, or as a tool by actual troops in the field. A tool capable of allowing actual troops to plan future and ongoing operations, and also evaluating current doctrines and tactics on the battalion level, would be beneficial. Problems occurred during the phases of the scenario building, model implementation, running the experiments and output generation.

- Generating the input files took a long time due for the scenario used in this research. Several spreadsheets had to be filled and had to be in harmony in order to avoid warnings when running the model. For example, the names of all of the 157 types of convoys had to be entered once on five different spreadsheets. As the names are case-sensitive and should be meaningful to avoid confusion, a large number of typographical errors occurred. The GUI, which was introduced during the International Data Farming Workshop, was used to detect errors in the spreadsheets. Building a scenario from the beginning using just the GUI would have avoided some errors and saved much time debugging.

- The LBC model has restrictions that can only be detected by implementing a wide range of scenarios. For example, it was not possible to send out an empty convoy and let it be loaded, and then return the convoy to the starting point. The model only accepted convoys that were loaded before the first move.
- Due to the missing DOE generating capability of the LBC model, the DOE had to be implemented using an additional spreadsheet and a VBA code to generate all input files.
- The input files that were generated were in the .xlsm file format, which cannot be run on Linux systems. They had to be converted to .xlm files in advance using the model's ability to convert from .xlsm to .xlm files.
- The random number seed cannot be set as a command line argument. That makes it impossible to re-run certain design points if necessary. This severely complicates the debugging process since it is not possible to re-examine a specific run of a specific scenario where problems are known to arise. Furthermore it makes it impossible to simulate different design points with the same random number seed to obtain a more precise comparison (Law, 2007).

- The run time of the experiments took from two minutes up to almost four days. The cause of these huge differences could not be explained. The random number seed issue prevented further exploration of this behavior.
- Running a shorter scenario (i.e., 240 hours of simulation time instead of 9,600 hours, and two replications instead of the initial ten replications) on design points one and two revealed no problems in regard to missing output or the memory use of the LBC model. Running all the experiments over the whole 9,600 hours with ten replications ended in a mean of just 4.19 replications that were completed. DP 1, for example, completed with ten replications, whereas DP 2 aborted after the fourth replication. A majority of the experiments completed four replications, while only eighteen completed all ten replications.



Quantiles

100.0%	maximum	10
99.5%		10
97.5%		10
90.0%		4
75.0%	quartile	4
50.0%	median	4
25.0%	quartile	4
10.0%		3
2.5%		3
0.5%		0
0.0%	minimum	0

Moments

Mean	4.1944444
Std Dev	1.5041223
Std Err Mean	0.0835624
Upper 95% Mean	4.3588396
Lower 95% Mean	4.0300493
N	324

Figure 21. Distribution and Summary Statistics of the Number of Replications Completed

- The model stopped producing output at some point and aborted, but did not give a warning message to the user. This fact was only discovered by a detailed look into output files and system log files. The cause for that problem was the limited memory of the high performance computer used. Assigning 1024MB Java heap memory in the command line, as initially tried, meant that some experiments stopped due to the fact that more memory was needed. Even the aggressive heap option of the Java virtual machine was not sufficient on the high performance computer at NPS, the Reaper, with 2 GB of memory. Finally, four design points had to be run on a computer with 12 GB RAM, of which 8.8 GB were used on a single experiment. Figure 22 shows a graph resulting from the LBC model's memory output file from DP 68. In this figure, the x-axis is the run time of the experiment for the three replications, the y-axis on the left shows the memory of the computer, ranging from 1 GB to 7 GB, and the y-axis on the right represents the number of real time seconds per hour of simulation time. The red line at the top shows the memory that is allocated by the computer system, which is slightly more than 6 GB. The green line shows the actual memory usage over the run time. The memory usage increases during a replication and then the garbage collector of the LBC model dumps information; but, as shown in the graph (provided by John Ruck, the lead programmer for the LBC model at TRADOC Monterey), some information is still stored at the beginning of the next replication. Exactly what information is stored is currently unknown, and must be investigated by the lead programmer for the LBC model. Having an even longer run time, either due to a more complicated scenario or due to a longer simulation time, would eventually make the green line hit the red line, resulting in an immediate termination of the experiment. The blue dots depict the number of real seconds used to simulate one hour of simulation time. It is also obvious that the LBC model's run time increases with the build-up of memory.

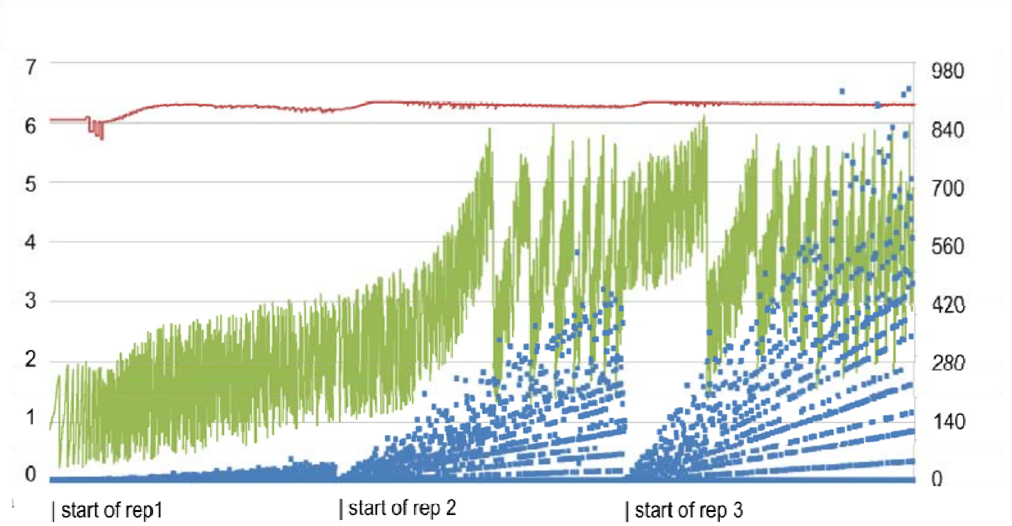


Figure 22. Memory Use of an Experiment

- Concatenating the output files and implementing the DOE to gain a single file that can be used by an analysis tool like the PASW Modeler 13 or JMP 8 was made easy with a Java tool that was built for this research. However, once again the large-scale experimental design was useful in verifying that the concatenation tool worked properly. Initially, graphical analysis indicated there were a few severe outliers in the reported MOEs for two design points (such as an average travel time of over 4800 hours). Looking into this further, we found the apparent outliers resulted from a miscalculation in certain instances. This led to recoding the concatenation tool to fix the problem. If a user assumed the tool was working properly and did not observe and investigate these apparent outliers, the results would have been changed to unreasonable results and the wrong conclusions could be drawn.

D. DETERMINISTIC ANALYTIC MODEL

If the LBC model was working properly, then the analysis of the LBC model's outputs would identify which factors and interactions have the largest affects on the mean traveling times for the convoys. In its present state, it does not help the German Armed Forces to make decisions about the actual number of transportation assets that are needed to support a mission with a certain level of commodities delivered.

In order to help the decision maker when planning a mission, we created a deterministic analytic model that is prototyped in a Microsoft Excel spreadsheet. This deterministic analytic model is described in detail in the Appendix. This spreadsheet model uses a large number of the input factors, including the number of transloading assets available, the capacities of the transportation vehicles, the distances from the LOGBASE to the receiving points, the demands of the three types of commodities, and the population sizes. For a comparison of the factors in both the spreadsheet model and the LBC scenario, see Tables 8-13 in the Appendix. Once these inputs are specified, the spreadsheet allows the user to specify a desired delivery schedule for each receiving point in terms of the number of resupplies within a six-day window, and the number of days of supplies (by commodity) for each delivery. Every one of the eight receiving points can be resupplied with any of the three commodities between one and six times within this six-day window, for example REC1 can be resupplied with water every day but with medical supplies just every second day.

For convoys traveling between the SPOD and the LOGBASE, there is more flexibility; economies of scale can be leveraged because the LOGBASE has storage capacity.

The subject matter expert, i.e., the logistician, can preset many of the input values. The outputs of this model include the number of semi-trailer trucks, DROPS trucks, and accompanying vehicles that are required, as well as the percentage of unmet demand by commodity for each receiving point, so that the logistician can use this information to decide how the convoys have to be set up. Furthermore it is also possible for him to prioritize the order of the receiving points being resupplied if there are not enough transportation assets available to resupply all receiving points at the same time.

For a scenario similar to the basecase used in the LBC model's experiments, the spreadsheet indicates that 172 semi-trailer trucks and 128 trucks of type DROPS are necessary to conduct the distribution operation if each receiving point is resupplied daily with one day's worth of demand, which corresponds to five transportation companies. Therefore, the transportation assets cannot be added to an additional platoon in the supply company, but at least one transportation company has to be added to the logistics battalion. This alternative is also easier to implement from an organizational perspective.

Five transportation companies may overestimate the number of trucks required, because of the assumption that assets from disbanded convoys do not become available until the next morning. More trucks are used than the number available for most of the design points in the LBC experiment, although it does not explain why convoys stopped completely in the LBC scenario rather than simply running less often. Subsequent test runs of the LBC scenario that were conducted with even higher numbers of transportation assets (i.e., 300 semi-trailer trucks and 300 DROPS trucks) still did not generate convoys over the whole simulation time of 9,600 hours. According to the spreadsheet model, running LBC with 300 trucks of each type should have resulted in convoys being generated during the whole simulation time.

As a result of this research, the top priority for TRADOC MONTEREY's support of the LBC model has shifted from adding additional features to LBC to isolating the causes for LBC's long run times, memory usage buildup, and inability to generate convoys across the entire length of time. The spreadsheet model is intended to assist the LBC lead programmer in this effort by providing baseline numbers to which the LBC model results can be compared.

Enhancements to the spreadsheet model are open to further work. For example, the spreadsheet model currently has no stochastic components. This is not an unreasonable simplification for assessing ongoing sustainment operations if the commodity levels, transloading assets, and transportation assets are plentiful. Clearly, if limited resources result in queuing delays, then a stochastic discrete-event model is more appropriate. Stochastic components could easily be incorporated into the analytic model for factors like transportation and planning times. Allowing the logistician to specify the number of receiving points, rather than fixing this at eight, would make this tool more general.

A simplified interface worksheet or “dashboard” is another potential enhancement to the spreadsheet model. This would provide logisticians with a simple decision-support that could be used in the field. A logistician could try out a few alternatives by hand when the mission situation changes and a quick response is needed.

After any desired enhancements are made, it would be possible to conduct an experiment on the spreadsheet model as was conducted for the LBC scenario. The analysis of such experiments can be approached as described earlier in this chapter, and would provide the transportation planner with more insights about which factors and interactions have the biggest effect on the MOEs. These insights, in turn, could streamline the planning process by providing the logistician with guidance about which combinations of inputs to focus on, rather than relying on a trial-and-error process. This is a subject for future research.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

This research explores a humanitarian assistance scenario involving the German Joint Support Service. The focus is on transportation and distribution operations from a seaport that provide aid to eight different receiving points via a theater logistics base. We employ a combination of modeling and simulation and statistical design of experiments to identify which are the significant factors for managing and allocating transportation assets. The scenario is implemented in a prototype version of the Logistics Battle Command (LBC) modeling platform developed by the U.S. Army Training and Doctrine Command Analysis Center in Monterey.

Ideally, logisticians should have a tool that facilitates rapid development of mission plans that reflect the commander's intent. The tool should also help them determine appropriate remedies in the face of unforeseen circumstances, such as weather delays, equipment failures, loss of materiel, and more.

The LBC model and the humanitarian assistance scenario are both quite complex, and we explored 131 factors to determine their relative impacts on three measures of effectiveness: (1) the average time to complete convoys between the sea base and the logistics base; (2) the average time to complete convoys between the logistics base and eight receiving points; and (3) the amounts of three commodities delivered. Understanding which of the 131 factors (and interactions among these factors) have the biggest affects on the measures of effectiveness (MOE) can provide guidance to the German Armed Forces about a suitable force structures for this specific mission. We used a highly efficient, custom-built experimental design due to the complexity of the factor space, and initiated 324 variations of the base scenario on high performance computers. Our original intent was to formulate recommendations for a suitable force structure for specific missions. However, significant shortcomings in the model were uncovered by our experimental design. In some cases, the root causes of these shortcomings could be identified and corrected by the lead programmers, but others are still under investigation. This emphasizes the importance of systematically exercising a model, particularly when extending its scope to new domains.

Despite the issues uncovered during the LBC investigation, we are able to provide limited insights about force structure based on a deterministic analytic model that is prototyped in a spreadsheet. Specifically, because of the large number of transportation assets required to meet the demand, an enforced supply company is not recommended for this scenario. Instead, transportation companies have to be added to the force structure. This is also the simplest alternative from an organizational point of view.

We show how partition trees and regression analyses can be used to gain insights about the most influential factors and interactions, but since the LBC model is not running properly, we caution the reader that these “findings” are for illustrative purposes only. It did appear that the number of semi-trailer trucks was one of the most influential factors. As most of the commodities are transported in containers, which can only be done using a semi-trailer truck and its trailer, it is obvious that the availability of this type of truck is limiting the distribution operation. The allocation of this type of trucks to either the supply company or to the transportation company did not appear to influence the outcome.

Following the semi-trailer trucks, the transloading assets needed to handle the containers were of great importance. The total number of the container handling devices was associated with ability of convoys to travel at all in an simulation run. Next to the total number of these assets and the number of forklifts within the logistics battalion, it is important to know how many of these assets are available to unload or upload a single convoy and its respective commodity, i.e., water, medical supply or non-military equipment. In this scenario, a small number of assets were allocated to unload or upload a single commodity within a convoy; interchanging these assets was not possible.

The prototype LBC model used in this research had to be debugged and updated frequently during the implementation phase and during the conducting of the simulation runs. The LBC model is not capable of modeling all possible logistics tasks up to this point and not all issues could be identified and resolved. For example, at first it was not possible to send an empty convoy to the SPOD and let him return loaded; the LBC model only allowed convoys to start loaded. Although a complicated and intensive scenario was constructed for this research, it only modeled the transportation aspects of a distribution operation; the aspects of maintenance and communication, and the impact of personnel on distribution operations and maintenance was not implemented. The execution of the simulation runs took a very long time (up to four days) and made it necessary to use computing resources with up to 12GB of memory. Using the LBC model not as a stand-alone model and integrating it into the Combat XXI could cause the Combat XXI model to slow down in an extreme manner. Furthermore, the LBC model cannot easily be used by a battalion in the field due to its long runtimes and its need for large computing resources.

Ideally, logisticians should have a tool that facilitates rapid development of mission plans that reflect the commander's intent. The tool should also help them determine appropriate remedies in the face of unforeseen circumstances, such as weather delays, equipment failures, loss of materiel, and more.

B. SIGNIFICANT CONTRIBUTIONS

Up until now, German Armed Forces decisions about the appropriate force structure for specific missions are made without conducting a simulation, and typically reflect the home force structure as given in the TO&E. Despite the shortcomings uncovered in the LBC model, it is clear that using modeling and simulation, combined with design of experiments techniques, could help logisticians assess the operational effectiveness of different strategies and improve the effectiveness of the logistics functions.

As a result of this research, the top priority for TRADOC MONTEREY's support of the LBC model has shifted from adding additional features to LBC to isolating the causes for LBC's long run times, memory usage buildup, and inability to generate convoys across the entire length of time. The spreadsheet model described in Chapter V Section D may assist the LBC lead programmer in this effort by providing baseline numbers to which the LBC model results can be compared.

Finally, we needed a highly efficient, custom-built experimental design due to the complexity of the factor space. Heuristic methods have been successfully used in previous studies, but broke down when faced with the large number of factors with a limited number of discrete levels. As a by-product of this work, an automated method for constructing nearly balanced NOLH designs has been developed (Vieira Jr., et al., 2010). This will be beneficial in future studies.

C. RECOMMENDATIONS

Resulting from analysis following recommendations can be made for the force structure of a logistics battalion in a humanitarian relief operation:

- Knowing about the demands of supplies during a humanitarian relief operation is essential in order to pre-calculate the number and types of transportation and transloading assets.
- Due to the large number of transportation assets needed an enforced supply company is not recommended in this scenario. Transportation companies have to be added to the force structure. This also makes it easier from an organizational point of view.
- Whether it is more effective to allocate the drivers to their vehicles or pool them could not be answered because the drivers did not show up as statistically significant factors in the analysis. However, operating experience shows that drivers will feel more responsible

for the vehicles if they are allocated to a specific vehicle, which will increase the operational availability due to better technical readiness.

Regarding the LBC model, the following recommendations can be made:

- The use of a large amount of memory should be reduced to run the model on computers that are widely available, even with a large and complicated scenario.
- It must be possible to change the random number seed in order to replicate simulation runs or to run replications of a design point on different computers.
- The GUI is needed to implement complicated scenarios into the LBC model and therefore should be developed further.
- The LBC model should be used for a broader spectrum of scenarios to find further issues the model cannot cope with.
- The implementation of personnel in the model (e.g., missing personnel due to illness, etc.) should be implemented.
- As mission planning for logistic tasks is important a model to gain insights in the driving factors has to be developed. Logisticians should be used to implement logistic scenarios in these models. Building a new model might be easier than identifying shortcomings and resolving problems with the LBC model. Regardless of the model used, thorough testing—using methods as in this research—is essential throughout the model development phase. It is particularly important when extending the scenarios into new domains. This will ultimately assure that the model provides relevant and accurate insights about this type of operations.

D. FUTURE RESEARCH

As previously noted, the prototype LBC model is not providing reliable results for this scenario, but the causes for this behavior are under investigation.

The following paragraphs list the possible future research questions that should be examined, either using the LBC model or another model:

First, the study only focuses on a humanitarian relief mission. The MOEs should be reconsidered in other scenarios, like missions involving military end-users in a peacekeeping force.

Second, the scenarios could be expanded to all concerns regarding maintenance (e.g., mean time between failures, mean down time, and availability of spares parts).

Third, troop leaders in the field would prefer a tool that yields an 80 percent solution in a short time in order to do a quick analysis when a situation changes. For example, the regression equations from the analysis of a pre-planned scenario could be incorporated in a spreadsheet to make it possible for logisticians to explore alternatives.

Fourth, in a similar vein, the analytic model could be enhanced in order to provide a decision-making tool that can be readily used in the field. As with any simulation tool, a designed experiment should be used to verify the model's performance and identify the model's strengths and limitations before it is fielded.

Fifth, planning time is a measure of effectiveness that should be considered. Shortening the planning time by adding more planning personnel might further increase the efficiency of distribution operations, but the trade-offs between cost and efficiency should be evaluated.

All logistic operations are highly important to any military mission. When using modeling and simulation techniques, as in this research, helping to increase the logistic efficiency is the main goal. At the end, logistics is not everything, but everything is nothing without logistics.

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APPENDIX: DETERMINISTIC ANALYTIC MODEL

In this appendix, we describe in detail a deterministic, analytic model that can be used to approximate the logistical assets required to conduct sustained humanitarian relief operations. The equations are simple enough to be captured in a spreadsheet, which makes this an accessible and potentially useful planning tool for logisticians.

A. ASSUMPTIONS

In field operations, logistics functions become much more complicated whenever uncertainty exists. Random events, such as equipment breakdowns and travel delays, can throw off logistics plans – particularly when convoy vehicles must form queues to access transloading assets and other shared resources. Expeditionary operations are particularly sensitive to random events. To summarize a child's nursery rhyme, "for want of a nail…a kingdom was lost." This emphasizes the importance of logistics, showing that failure to make deliveries in a timely manner can alter the outcome of an entire operation.

In contrast, the operation investigated in this thesis is a sustained humanitarian relief effort. The performance of the logistics system is not measured in terms of battles won or lost, but rather in terms of how well the needs of the population are met, and the logistical resources required. We assume that, over the long term, there are unlimited commodities at the SPOD, and enough transportation assets to implement the desired humanitarian relief plan. In the short term, if insufficient resources are available, the logistician can use the tool to assess various expediting options.

B. MODEL INPUTS

The model has 92 input factors. In Tables 8 to 13, we provide a summary of these inputs, and indicate how they relate to the LBC factors described in Chapter IV Section B.

Factors	Description	Basecase factor levels	Number of DM factors	Related LBC factor	Basecase factor levels	Number of LBC factors
I_i (i=1,…,8)	Inhabitants of receiving point *i*	500 - 5530	8	Inhabitants of receiving point *i* (noise factors 1-8)	500 - 5530	8
I_{LB}	Population at LOGBASE	400	1	Not varied	400	0
$PLAN_{LB}$ $PLAN_{SPOD}$	Number of planning personnel at LOGBASE and SPOD, respectively	1 1 (normalized)	2	BDE, BN, SC, and TC planning personnel (decision factors 1-3, 15)	various	4
$TREC_i$ (i=1,…,8) $TSPOD$	Travel time from LOGBASE to receiving point *i* and LOGBASE to SPOD	3.6– 11 hrs, 37.8 hrs	9	Probability short time "move to" (noise factor 38) modifies base travel times	3.6– 37.8 hrs base average times, 0.50 base prob	1
W M NM	Daily demand rate of water, medical, and non-military supplies, per person	6 kg 0.2 kg 4 kg	3	Daily demand rates of water, medical, and non-military supplies per person (noise factors 9, 10, 12)	6 kg 0.2 kg 4 kg	3

Table 8. Input Factors of the Deterministic Analytic Model with Relations to the LBC Model

Factors	Description	Basecase factor levels	Number of DM factors	Related LBC factor	Basecase factor levels	Number of LBC factors
S	Daily demand rate of spare parts, per soldier	3 kg	1	Daily demand rate of spare parts, per soldier (noise factor 11)	3 kg	1
P_{LB}	Total daily planning time at LOGBASE	1.5 hrs	1	Probability short time "plan" (noise factor 37) and number of personnel modify base planning time	1.5 hrs with basecase planning personnel	1
P_{SPOD}	Total daily planning time at SPOD	1.5 hrs	1	All planning assumed to occur at LOGBASE		0
$DRIVERS$	Number of drivers	unlimited	0	Sum of drivers by company, vehicle type (decision factors 8-11, 19-21)		7
$NSEMI$ $NDROPS$	Number of trucks	unlimited	0	Sum of trucks by company, vehicle type (decision factors 4-7, 16-18, 25-28)		11

Table 9. Input Factors of the Deterministic Analytic Model with Relations to the LBC Model (continued)

Factors	Description	Basecase factor levels	Number of DM factors	Related LBC factor	Basecase factor levels	Number of LBC factors
TA_{LB}	Number of transloading assets at LOGBASE	16	1	Sum of forklifts and container-handling devices at LOGBASE, upload and download, all destinations (decision factors 12-13, 61-88)		30
TP_{LB}	Number of transloading operators at LOGBASE	unlimited	0	Forklift and container-handling operators at LOGBASE (decision factor 14)		1
TA_{SPOD}	Number of transloading assets at SPOD	16	1	Sum of transloading devices at SPOD, upload and download (decision factors 23-24, 57-60)		6
TP_{SPOD}	Number of transloading operators at SPOD	unlimited	0	Transloading operators at SPOD (decision factor 22)		1

Table 10. Input Factors of the Deterministic Analytic Model with Relations to the LBC Model (continued)

Factors	Description	Basecase factor levels	Number of DM factors	Related LBC factor	Basecase factor levels	Number of LBC factors
DW *DM* *DN*	Download time for water, medical, and non-military supplies, common for all receiving points	1.66 hrs 0.33 hrs 2 hrs	3	Download assets at receiving points (noise factors 13-36) and Probability "short time" download (noise factor 42) modify total download time	1.66 hrs	25
DLBW *DLBM* *DLBNM* *DS*	Download time for water, medical, non-military supplies, and spare parts at LOGBASE	0.3 hrs 0.3 hrs 0.3 hrs 0.05 hrs	4	Transload assets at LOGBASE and Probability "short time" download (noise factor 42) modify total download time	0.3 hrs 0.3 hrs 0.3 hrs 0.05 hrs 0.5 base prob	0*
ULBW *ULBM* *ULBNM*	Upload time for water, medical, and non-military supplies at LOGBASE	0.443 hrs 0.443 hrs 0.443 hrs	3	Transload assets at LOGBASE and Probability "short time" upload (noise factor 41) modify total download time	0.443 hrs 0.443 hrs 0.443 hrs 0.5 base prob	1

Table 11. Input Factors of the Deterministic Analytic Model with Relations to the LBC Model (continued)

Factors	Description	Basecase factor levels	Number of DM factors	Related LBC factor	Basecase factor levels	Number of LBC factors
USPODW *USPODM* *USPODNM* *USPODS*	Upload time for water, medical, non-military supplies, and spare parts at LOGBASE	0.443 hrs 0.443 hrs 0.443 hrs 0.05 hrs	4	Transload assets at SPOD and Probability “short time” upload (noise factor 41) modify total download time	0.443 hrs 0.443 hrs 0.443 hrs 0.05 hrs base times, 0.5 base prob	0*
$C_{LB\text{-}SPOD}$ $C_{LB\text{-}REC}$	Maximum number of transport vehicles in convoys	12 10	2	Convoy composition varies by type of vehicle, commodity, (decision factors 29-56)	various	28
FORM *DISBAND*	Not modeled separately: included in convoy planning and formation time	N/A	0	Probabilities short time “form convoy” and “dispand convoy” (noise factors 39, 43) modify total times	0.45	2

Table 12. Input Factors of the Deterministic Analytic Model with Relations to the LBC Model (continued)

Factors	Description	Basecase factor levels	Number of DM factors	Related LBC factor	Basecase factor levels	Number of LBC factors
SEIZE	Not modeled separately: included in convoy planning and formation time	N/A	0	Probability short time "seize assets" (noise factor 40) modifies total time to prepare for convoy uploads and downloads	0.45	1
$SCHEDW_i$ $SCHEDM_i$ $SCHEDNM_i$	Max scheduled delivery days per six-day period, by receiving point	1, 2, 3, or 6	24	Deliveries are outputs, not inputs	N/A	0
$DAYSW_i$ $DAYSM_i$ $DAYSNM_i$	Max days of demand in a given delivery, by receiving point	1, 2, 3, or 6	24	Trucks travel loaded if there are unmet needs at receiving points	N/A	0
TOTALS			92			131

Table 13. Input Factors of the Deterministic Analytic Model with Relations to the LBC Model (continued)

With these factor descriptions, we can calculate several performance measures of interest. Our assumptions follow.

1. There are sufficient resources (trucks, drivers, and transloading assets) available, on average, for a sustained humanitarian assistance effort. This implies that the total amount delivered from the SPOD to the LOGBASE is equal to the total need during a longer time period (12 days in this scenario).

2. The LOGBASE has facilities capable of storing at least a twelve-day supply of all commodities needed at the LOGBASE and all receiving points. Unmet demand at the LOGBASE is not permitted.

3. The upload and download times per day at the LOGBASE and SPOD do not vary by the type of vehicle or the amount loaded on that vehicle.

4. The net time spent uploading and downloading at the LOGBASE and SPOD can be approximated by the total time spent uploading or downloading, divided by the number of transloading assets. Specifically, this does not account for additional delays due to queue buildups, or for the discrete nature of the transloading operations (e.g., at most one transloading asset can be used for each vehicle).

5. Planning occurs at the beginning of each day, and then convoys are formed and dispatched. Convoy assets (trucks and drivers) are considered to be “in use” until the beginning of the day following their return to the LOGBASE.

6. Calculations assume that the convoys are balanced as needed. For example, if each receiving point is resupplied once in every six-day period and each round trip takes less than 24 hours, then staggering the delivery days uses one-sixth the resources required

for synchronized deliveries. Similarly, if the plan is to resupply a receiving point three times per six-day period with a two-day supply, the deliveries are staggered so they all occur on even-numbered (or all on odd-numbered) days.

7. Each truck can carry only one type of commodity during a single convoy, but any truck can carry any commodity. In any given convoy, at most one truck for each commodity is carrying less than a full load.

Consider receiving point i (RECi). Let $TOTW_i$ denote the total six-day demand for water. Then

$$TOTW_i = 6 * I_i * W$$

and the maximum water that can be delivered at one time is

$$MAXW_i = DAYSW_i * I_i * W.$$

Let $SEMIW_i$ and $DROPSW_i$ denote the number of trucks of each type required for a single delivery, and let

$$SEMIW_i^* = \lceil MAXW_i / 25000 \rceil$$

denote the smallest number of semi-trailer trucks capable of transporting $MAXW_i$. The "most efficient loading" uses as few trucks as possible and sends trucks as close to fully loaded as possible, given the limitation on the number of days of supply provided at one point in time. Mathematically, the most efficient loading occurs when

$$DROPSW_i = \begin{cases} 2 \text{ if } MAXW_i - 25000 SEMIW_i^* \geq 22000, \\ 0 \text{ if } MAXW_i - 25000 SEMIW_i^* < 11000, \\ 1 \text{ otherwise.} \end{cases}$$

and

$$SEMIW_i = SEMIW_i^* - DROPSW_i.$$

Other loadings are calculated, such as those using only *DROPS* trucks. The total number of deliveries is

$$DELIVW_i = \min\left\{SCHEDW_i, \frac{6}{DAYSW_i}\right\}$$

during each six-day period. The round-trip time between the LOGBASE and RECi , in days, is

$$MOE_2 = \left\lceil ULBW_i + 2TREC_i + 9\left\lfloor \frac{1}{9}TREC_i \right\rfloor + \max\left\{DW, DM, DN\right\} \right\rceil$$

and accounts for the upload time at the LOGBASE, travel time, rest time en route, and the download time at the receiving point. The numbers of trucks in use, on average, over each six-day period are

$$UsedSEMIW_i = SEMIW_i * DELIVW_i * DAYSW_i$$

and

$$UsedDROPSW_i = DROPSW_i * DELIVW_i * DAYSW_i$$

The multipliers compensate for the need for extra vehicles if the distance to the receiving point means that multiple convoys are traveling at the same time in order to meet the scheduled deliveries. Finally, the unmet demand for water during the six-day period is

$$UnmetW_i = TOTW_i - MAXW_i * DELIVW_i$$

The same approach is used for the other commodities at receiving point i , as well as commodities at the other receiving points. For convoys between the LOGBASE and the SPOD, deliveries are computed over a twelve-day window and there is no limit on the number of days of commodities supplied at one time.

Once the numbers of trucks have been calculated, by receiving point, for each commodity, they are formed into convoys based on the maximum number of transport vehicles per convoy; convoys between the LOGBASE and SPOD can have a different cap than convoys between the LOGBASE and the receiving points. For example, the number of convoys started over a six-day period between the LOGBASE and RECi is

$$CONVW_i = \left\lceil \frac{1}{C_{LB-REC}} * \left(UsedDROPSW_i + UsedDROPSM_i + UsedDROPSN_i\right) \right.$$
$$\left. + \frac{1}{C_{LB-REC}} * \left(UsedSEMIW_i + UsedSEMIM_i + UsedSEMIN_i\right) \right\rceil$$

The $CONVW_i$'s can be used to calculate the average number of escort vehicles in use. Finally, the unmet demand can be calculated across all receiving points by commodity, along with the total unmet demand.

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